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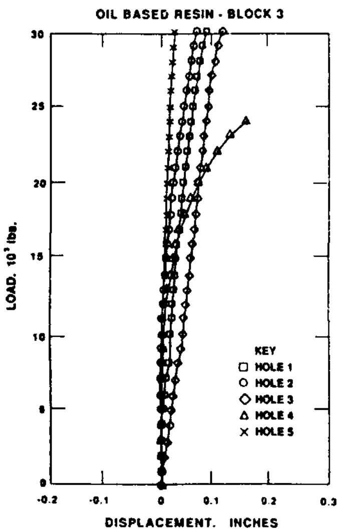

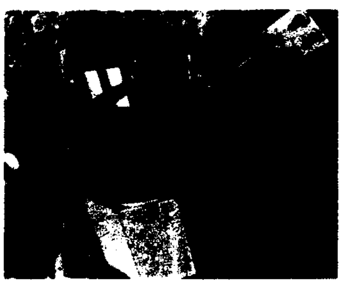

REMR RESEARCH PROGRAM

REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

TECHNICAL REPORT REMR-GT-17

APPLICATIONS AND TESTING OF RESIN GROUTED ROCKBOLTS

by

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January 1992

Final Report

Approved for Public Release; Distribution Unlimited

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Monitored by Geotechnical Laboratory
US Army Engineer Waterways Experiment Station
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

Under Work Unit No. 32413

The following two letters used as part of the number designating technical reports of research published under the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program identify the problem area under which the report was prepared:

	Problem Area		Problem Area
CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

COVER PHOTOS:

TOP — Air track drill.

MIDDLE — Displacement versus load-oil based resin.

BOTTOM — Jack and instrumentation for pull test.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	January 1992	Final report

4. TITLE AND SUBTITLE

Applications and Testing of Resin Grouted Rockbolts

5. FUNDING NUMBERS

DACW39-89-M-2338
Work Unit No. 32413

6. AUTHOR(S)

Timothy S. Avery
James E. Friant

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

J. E. Friant and Associates
1352 S.W. 175th Street
Seattle, Washington 98166

8. PERFORMING ORGANIZATION REPORT NUMBER

Technical Report
REMR-GT-17

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

USAE Waterways Experiment Station
Geotechnical Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

See reverse.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A few instances of rockbolt failure have been reported where polyester resin had been used as the anchoring grout. All reported instances involved submerged installations. A TVA test report confirmed that in a short hole (15 in.), under submerged conditions, the water can interfere with resin polymerization. This document reports additional laboratory and field tests which showed that water interference is confined to a short zone at the resin-to-water interface. Tests employing a grout length of 2 ft or more, on No. 6 rockbolts held their yield load, wet or dry.

Larger scale testing at the Bonneville Locks showed similar results. At grouting lengths of about 55 in. or more, yield load on a No. 11 rockbolt was reached, wet or dry.

(Continued)

14. SUBJECT TERMS		15. NUMBER OF PAGES
Anchors	Rock support	107
Polyester Resin	Underwater	16. PRICE CODE
Rockbolts	construction	

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

11. Supplementary Notes.

This is a report of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. Report is available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

13. (Concluded).

This report finds no deficiency in polyester resin grouted rockbolts or anchors, so long as proper procedures governing installations are followed. The conclusions and recommendations of this report contain suggested procedures and cautions.

PREFACE

The work described in this report was authorized by Headquarters, US Army Corps of Engineers (HQUSACE), as part of the Rock Problem Area of the Repair, Evaluation, Maintenance and Rehabilitation (REMR) Research Program. The work was performed under Work Unit No. 32413 entitled "Assessment of the Long- Term Performance Characteristics of Resin Grouted Rockbolts," for which Mr. Timothy S. Avery was Principal Investigator. Mr. Lewis A. Gustafson (CECW-EG) was the REMR Technical Monitor for this work.

Mr. Jesse A. Pfeiffer, Jr. (CERD-D), was the REMR Coordinator at the Directorate of Research and Development, HQUSACE; Mr. James E. Crews (CECW-O) and Dr. Tony C. Liu (CECW-EG) served as the REMR Overview Committee; Mr. William F. McCleese (CEWES-SC-A), US Army Engineer Waterways Experiment Station (WES) was the REMR Program Manager. Mr. Jerry S. Huie was the Problem Area Leader.

The report was prepared by J. E. Friant and Associates, Seattle, Washington, under Purchase Order No. DACW39-89K-0010. The principal authors of this report were Messrs. Timothy S. Avery and James E. Friant. Mr. Avery was Principal Investigator (PI) during his employment at WES. Ms. Eileen Glynn (WES) was PI for the last year of the study and conducted the long-term laboratory creep tests. Messrs. Perry A. Taylor, Ricky Steed, Lester R. Flowers, and Robert F. Anderson, all of WES, assisted in the laboratory study.

The work was under the direct supervision of Mr. Jerry S. Huie, Chief, Rock Mechanics Branch, and under the general supervision of Dr. Don C. Banks, Chief, Soil and Rock Mechanics Division (S&RMD), and Dr. William F. Marcuson III, Chief, Geotechnical Laboratory (GL), WES. Dr. Paul F. Hadala, Assistant Chief, GL, was Senior Technical Reviewer.

COL Larry B. Fulton, EN, was Commander and Director of WES. Dr. Robert W. Whalin was Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic yards	0.7645549	cubic metres
feet	0.3048	metres
inches	2.54	centimetres
kips (force)	4.448222	kilonewtons
pounds (force)	4.448222	newtons
pounds (force) per inch	175.1268	newtons per metre
pounds (force) per square inch	6.894757	kilopascals

APPLICATIONS AND TESTING OF RESIN GROUTED ROCKBOLTS

PART I: INTRODUCTION

1. In the United States, the market for rockbolts and anchors is estimated to be in excess of 100 million units per year. The rockbolts are used for roof support in tunnels and mines, stabilizing high walls, anchoring structures to bedrock, and other applications requiring the basic "fixing" of an excavated rock face. In rehabilitation work, the rockbolt is frequently used for anchoring new construction to an old, but still competent, concrete base structure.

2. Of the total rockbolt market, nearly one-half is installed using polyester resin. This type of bolt is economical, easy to utilize, fast setting, and uses a minimum of auxiliary support equipment.

3. The installation of all types of rockbolts involves three basic and common steps:

   a. Drilling a hole to a specified depth.

   b. Inserting a rockbolt, nearly always steel.

   c. Locking the bolt into place.

4. The largest variation in procedure involves locking the bolt into place. This is accomplished by wedging, cement grouts, resin grouts, deforming a hollow bolt with high pressure, or even by friction through a spring-loaded bolt.

5. Developed as a grout in Europe in the mid 1960's, polyester resin was introduced into the United States as an anchor grout material in the mining industry in the early 1970's. At modest cost, new or unstable areas in coal mines could be safely supported in a matter of minutes using polyester resin grouted rockbolts.

6. At first, the resin was used only at the end of the hole, functioning much as the mechanical bolt anchor it replaced. As the concept of beam building developed, fully grouted bolt columns and the procedure of pretensioning the bolt were developed. This latter procedure was accomplished by using resins of varying set time so that the end of the bolt set and the pretensioning could be applied while the resin in the remainder of the hole was still tacky.

7. Typical bolts ranged in length from 4 to 8 ft*, and were usually 3/4-or 7/8-in. diam grade 60 steel. The ease of installation, strength, and almost instantaneous set time of the resin caught the attention of the heavy construction industry. The Corps of Engineers' Clarence Cannon Dam in Missouri, the Bureau of Reclamation's Navajo Tunnel in New Mexico, and the Colorado Department of Highway's Straight Creek (Eisenhower) Tunnel were among the first construction projects to use polyester resin.

8. The use of polyester resin grouted rockbolts in the construction industry has been widely accepted since its introduction. Today, the resin is the most commonly used grout material and is used with 20, 40, and sometimes even 90 ft long rockbolt applications. The basic concept of polyester resin's use still seems to be:

borehole + rockbolt + resin = anchor

9. The acceptance and use of the resin grouted rockbolt as a construction anchor were so rapid, application literally outstripped research and guidelines for its use. As a result, the quality and performance of the resin grouted rockbolt may reflect not only the experience level of the installer (generally a drill operator) but also the accuracy of the installation guidelines which he is following.

Purpose and Scope

10. This report focuses on the polyester resin grouted rockbolt and its application as an anchor for securing structures to bedrock or old foundation work. After wide spread use over many years, suspect resin grouted anchors were discovered at Old River Control Structure (McDonald 1980) and at Lock 3 Monongahela River (Krysa 1982). Both these applications involved submerged rockbolt installation.

11. If an inherent problem exists, which casts doubt on the integrity of all submerged installations of resin grouted rockbolts, many Corps of Engineers projects have serious problems. To discover the extent of the problem, literature searches plus both laboratory and field tests were conducted. The intent was to determine any parameter which could affect the general integrity of rockbolts which may now be a critical part of existing

* A table of factors for converting non-SI units of measurement to SI (metric) units is found on page 3.

structures. This report summarizes the findings on four series of bolt tests plus provides general information on the critical factors for resin grouted rockbolt use.

Background

Basic resin rockbolting procedure

12. Drilling. The basic requirements of a drill used to create the hole for a resin grouted rockbolt are that the drill forms the hole as rapidly as possible, reasonably straight, and with a rough surface. The hole roughness is required to assure a good mechanical interlock between the resin and the native rock. These requirements suggest that a rotary-percussive (R-P) type drill be used. The R-P drill must also have sufficient thrust and torque to push and spin the bolt into a resin cartridge filled hole within the time required for proper resin mixing.

13. Common rockbolt (or bolt) sizes are No. 6 through No. 14. Holes should generally be drilled from 1/4- to 1/2-in. oversize as shown in Table 1 below.

Table 1

Bolt and Hole Sizes

Bolt Size No.	Bolt Diameter, in.	Bore Sizes, in.
6	3/4	1 to 1-1/8
7	7/8	1-1/8 to 1-3/8
8	1	1-1/4 to 1-1/2
9	1-1/8	1-1/2 to 1-3/4
10	1-1/4	1-5/8 to 1-7/8
11	1-3/8	1-3/4 to 2
14	1-5/8	2-1/4

14. Resin installation. Polyester resin is conveniently packaged in a "sausage-like" cartridge. The package is generally mylar and contains both resin and catalyst in separate compartments. Cartridges are coded reflecting their size, viscosity, and set time. As a rule, the best practice is to completely fill the void space between the bolt and the hole with resin. This

practice not only provides the maximum anchoring strength and reliability but also protects the bolt from corrosive effects by completely coating it with resin. The manufacturers of the cartridges provide convenient tables which have precalculated the number of cartridges required for any length of hole and any reasonable combination of hole and bolt size.

15. The proper number of cartridges are simply charged (pushed) into the hole. Up-holes require a "hat" or "spider" to hold the cartridges in place. In general, one or two fast-set cartridges are initially inserted into the hole, followed by the proper number of normal set time cartridges.

16. Polyester resin is a two-component system consisting of resin and catalyst encased in a mylar tube. When a spinning bolt penetrates the cartridge, the mylar tube should be shredded and incorporated into the resin. Currently, resins are either oil based or water based, the latter being slightly cheaper and predominantly used in the mining industry. Water or oil base refers to the carrying agent used for the benzyl peroxide catalyst. When dispersed through the polyester resin, the catalyst creates heat and causes the resin to polymerize and cure to a solid state.

17. The ambient temperature will either increase or decrease the resin catalyzation time. Higher temperatures will accelerate the reaction while low temperatures will slow down the reaction. In extreme heat or cold, efforts should be undertaken to keep the resin and bar at a constant temperature of approximately 55° F to 65° F. A resin system that is too hot may set up before the bolt is completely installed. A cool resin system may take too long to set up, and, if it is too cold, the resin may never cure to its full ultimate strength.

18. Contrary to a popular belief, polyester resin is not a glue. Polyester resin holds a rockbolt in place by friction. The asperities in the borehole wall grip the resin grout bulb when the bolt is stressed. The resin holds the rockbolt in place by the deformations on the bar. There is virtually no adhesion between polyester resin and the borehole wall, as there is with epoxy resins and cement grout. Polyester resin, once properly mixed, forms a hard, strong cylinder in the borehole which mechanically interlocks with the asperities of the borehole wall.

19. Good practice calls for "stressing" the bolt after the fast-set resin has hardened but before the normal resin sets up. A "stress" test is simply pulling on the bolt and measuring displacement. Stressing serves to

test the bolt before all the resin is totally set up. If the plate and fastener are assembled while the bolt is in tension, a preload is placed on the bolt. In most anchor applications a preload is desired.

20. Bolt insertion. The most common and convenient tool to utilize is the drill. The bolt can then be rotated slowly at the same time as thrust is applied. Depending on the bolt and hole sizes used, this thrust can be considerable. The bolt should be rotated during insertion and for a time after the bolt is bottomed out. Different resin manufacturers provide recommendations which may vary. For example, Celtite recommends rotation at 100 rpm for 30 sec after bottoming while Dupont recommends 600 rpm for 10 sec after bottoming.

21. The time allowed for the quick-set resin must be judged, as set time is so dependant upon ambient temperature of the rock and bolt. Between the quick-set and normal-set time, the bolt may be stressed to verify adequate pull strength and, if desired, locked off (plate and nut installed) to preload the bolt.

22. When the quick-set resin has polymerized, the bolt is ready to be utilized for plates, straps, or as a permanent anchor. Once the resin is completely set up. the pull strength of the bolt does not materially increase with time. If installed properly, the bolt will fail in tension before the force to extract the resin bulb is reached.

23. Geologic considerations. The ideal rock condition might be described as a granitic material with a compressive strength in the 15- to 20-ksi range and with few fractures and little water. Standard rockbolting techniques are adequate for standard rock conditions. Unfortunately, in nature, standard conditions are rarely encountered. Rockbolt design in terms of diameter of the bolt, length of the bolt, and anchoring detail must be evaluated for the characteristics of the particular site. Further, in practice, a "site" may be confined to a surprisingly small zone of a single rockbolting project. Site conditions change rapidly and must be continually evaluated. Good rockbolting practice becomes an iterative process. Each installation should utilize the experience of the prior installations. The factors having the greatest effect upon rockbolt performance are:

a. Rock strength.
b. Rock mass conditions.
c. The presence of water.

24. This report is not intended to be a complete dissertation on the

theory of rockbolting, but comments are included here to caution and make the reader aware of the most critical factors.

<u>a</u>. <u>Rock strength</u>. The pullout strength of a bolt is a function of rock strength times a constant, the grouted bolt length, and the bolt diameter. When length and diameter are expressed in inches, the constant is about 0.1 times unconfined compressive strength (UCS), expressed in pounds per square inch (psi), for strong rocks and will increase to 0.2 or 0.3 times UCS in weak rocks (Littlejohn and Bruce 1975-1976).

<u>b</u>. <u>Rock mass</u>. The rock mass is also an important factor in the anchor design when using polyester resin. Resin manufacturers calculate resin coverage based on a 15 percent resin loss. This resin loss is conservative for intact or tightly jointed rock but may seriously underestimate the resin loss in rocks with open joints. More resin cartridges must be used in holes with greater void space to fully encapsulate the bolt. In extremely fractured conditions, pregrouting the borehole with cement and redrilling it while the cement is still green may be a required step.

<u>c</u>. <u>Water presence</u>. The presence of water in the rockbolt borehole may pose additional problems. Water may be encountered in two states -- "static" or "dynamic." Static water refers to water that is ponded in or above a borehole, while dynamic water refers to water that is flowing from the rock through or out of the borehole. The two water conditions affect the performance of a resin grouted bolt differently. In severe cases of dynamic water, a prerequisite step of pressure pregrouting the borehole with a cement or silicate grout may be required to stem the flow. In a case of static water or minor flow, simple installation precautions and perhaps a slightly longer borehole will counter any deleterious effects of the water. This last case is the principal subject of this report.

<u>Dry installation</u>

25. The application of polyester resin grouted rockbolts in rehabilitation of concrete structures has been widely accepted. The rehabilitation of navigation locks involving removal and replacement of deteriorated concrete from the walls is a typical example. Dowels (rockbolts) are normally used to anchor the new concrete facing to the existing structure and to position reinforcing steel in the new concrete. In most cases, these dowels are grouted into place using polyester resin cartridges.

26. The dowels are normally grouted 1 to 2 ft into the old but competent concrete structure. Dowels in this case are usually installed under dry conditions and no significant number of failures have been reported.

Submerged installation

27. The use of polyester resin under submerged installation conditions at the Old River Control Structure was reported by McDonald (1980). The bolts were used to anchor a 12-in. steel module plate positioned between the downstream row of baffles and the end sill. Eight months following installation of the anchors, a diver inspection showed that some of the anchors had (a) broken flush with the module plate, (b) broken flush with the grout, or (c) pulled completely out of the concrete. The first two failure modes imply a satisfactory grout strength which exceeded the bar strength. The third failure mode implied a grout failure.

28. Another instance of submerged installation was summarized by Krysa (1982). Polyester resin was substituted for cement grout in the anchor length of post-tensioned anchors for lock wall stabilization at Lock 3, Monongahela River. A 1-1/4-in. diam bar was installed in a 2-1/4-in. hole using a recommended 45-mm diam resin cartridge. The rock in the anchor zone was fractured and water filled. The contractor was unable to stress 35 of these anchors to the design load. As a result, 18 anchors were accepted at reduced loadings and the remainder were replaced.

29. A failed anchor was removed and examined to determine a cause. Only the lower 5 ft of the bar was grouted. Most of the polyester resin grout on the bar was light gray and was easily removed. In other portions of the bar, the resin was harder and not as easy to remove from the bar. One possible explanation was that the drill hole had widened during drilling, thus impairing resin mixing. However, after sections of the hole were overcored and removed, it was found to be a consistent 2-1/4-in. diam.

30. The questionable performance of polyester resin under submerged installation conditions prompted a Repair, Evaluation, Maintenance, and Rehabilitation (REMR) investigation by the Structures Laboratory at WES. Actual testing was conducted at the Tennessee Valley Authority's (TVA) Singleton Materials Laboratory, in Knoxville, Tennessee. The results showed that, under the conditions tested, concrete anchors grouted with polyester resin under submerged conditions showed a considerable loss of pullout strength and much higher creep rates when compared with similar anchors installed under dry conditions.

Statement of the problem

31. Both of the projects discovered with faulty or suspect resin

grouted rockbolt anchors involved submerged installations. The results of the TVA tests raised further questions as to the performance of polyester resin grouted concrete anchors installed under submerged conditions. Since many Corps of Engineers projects have employed polyester resin rockbolt installations in wet or damp holes, the safety and performance of many existing structures might be questioned.

32. The prospect of a general requirement to replace and repair existing resin grouted rockbolts, where installed in wet conditions, would be both difficult and staggeringly expensive. Additional investigation and understanding of the problems were essential.

PART II: EVALUATION PROGRAM

Singleton Materials Engineering Laboratory Tests

33. In April 1985, WES awarded a contract to the TVA to compare the performances of cement, epoxy, and polyester anchor grouts when installed and cured under various conditions. Anchors were installed in concrete cylinders under both dry and submerged conditions. Test methods and results were presented in detail in the final report by Best and McDonald (1989). The following discussion is a review and brief analysis of this work.

Test setup

34. The tests were conducted in 18-in. long by 6-in. diam concrete cylinders. A 15-in. deep, 1-in. diam hole was drilled into each cylinder and a 3/4-in. diam reinforcing bar was grouted into each hole. All three grout types were used to embed anchors under dry conditions. Bars were also grouted with cement and polyester resin under submerged conditions. The epoxy resin was installed only in wet holes as the manufacturer specifically recommends against underwater installation with epoxy. Wet holes were obtained by keeping the drilled hole filled with water until just before grouting, pouring the water out, and installing the bar.

35. Following grouting, the test specimens were cured under either wet, dry, or alternately wet and dry conditions. Pullout tests were then conducted at 8 ages varying from 1 day to 32 months. In general, three specimens were tested for each casting and curing condition at a given age.

Test matrix

36. The TVA conducted five test series. The first involved tests on the grout itself and is not of interest here.

a. Series 2. This was a short-term test series conducted on samples prepared as follows:

Grout Placing Conditions	Curing Temperature, °F	Curing Condition after Grouting
Dry	70	Continuously dry
Submerged*	70	Continuously submerged
Submerged*	40	Continuously submerged
Dry	70	Continuously submerged
Dry	40	Continuously submerged

* Except for epoxy placed under wet conditions.

Three specimens for each of the above conditions were prepared and pullout strength tests were conducted at 1, 3, and 7 days age.

b. Series 3. This series involved long-term cure times, up to 32 months. Samples were prepared as follows:

Grout Installation	Cure Condition
Submerged*	Continuously submerged
Submerged*	Alternating wet-dry (7-day cycles)
Dry	Continuously submerged
Dry	Continuously dry
Dry	Alternating wet-dry (7-day cycles)

* Except for epoxy placed under wet conditions.

Pullout strength tests were conducted at 1, 3, 6, 16, and 32 months.

c. Series 4. Six specimens were grouted with each grout type. Three anchors were embedded in dry holes and the other three were embedded underwater (except for the epoxy). Pullout specimens were subjected to a 6-month creep test at a sustained load of 60 percent of the yield strength of the reinforcing bar. Specimens grouted under dry conditions were tested dry while those specimens grouted wet or submerged were tested under submerged conditions.

d. Series 5. Limited tests were conducted to evaluate the effect of hole roughness and cleanliness on 28-day pullout strengths. Vertical holes drilled with both diamond-tipped core barrels and rotary percussion bits were grouted underwater (except for the epoxy). One-half of the holes was cleaned of debris and cuttings prior to grouting and the remaining one-half was left uncleaned.

Results

37. Polyester resin. The overall average pullout strength of specimens placed and cured under submerged conditions was 35 percent less than the strength of specimens placed and cured under dry conditions. Although not explained, the largest reductions, approximately 50 percent, occurred at the ages of 6 and 16 months. Compared with submerged placing and curing, alternating 7-day cycles of submerged and dry curing resulted in approximately 10 percent higher pullout strength. Grout placement and curing at 40° F had no significant effect on pullout strength.

38. Epoxy resin. Pullout strengths were essentially equal to the ultimate strength of the reinforcing-bar anchor regardless of placing and curing condition. The overall average pullout strength of specimens placed

and cured under wet conditions was 1 percent less than the strength of similar specimens placed and cured under dry conditions.

39. Cement. Beyond 1-day age, the pullout strengths of cement grouted specimens were essentially equal to the ultimate strength of the anchor regardless of grout placing or curing conditions.

40. Series 4, creep tests. After 6 months under load, the cement and epoxy grouts placed, cured, and tested under dry conditions exhibited very low bar slippage, averaging 0.0013 and 0.0008 in., respectively. In comparison, the polyester resin grout exhibited an average bar slippage of 0.0305 in., approximately 30 times higher than the cement and epoxy grouts.

Results of creep tests on specimens fabricated and tested under wet conditions followed a similar trend. After 6 months under load, the average bar slippage for the cement and epoxy grouts was 0.0028 and 0.0033 in., respectively, or two to three times higher than results under dry conditions. Polyester resin grout specimens, fabricated and cured under wet conditions, exhibited significant slippage; in one case, the bar pulled completely out of the concrete after 14 days under load. After 6 months under load, the two remaining specimens exhibited an average bar slippage of 0.0822 in., approximately 30 times higher than the cement grout.

41. Cleanliness. Leaving cuttings and debris in percussion-drilled holes resulted in reduced pullout strengths for all three grouts. As shown below, compared with clean installations, dirty holes compromise the strength of rockbolts.

Grout Type	Pull Strength Loss
Polyester	5 percent
Epoxy	70 percent
Cement	27 percent

No significance is placed on the different strength reductions, but the significance of a clean borehole with any grout is clear.

42. Summary. The results of these tests confirmed that water in the anchor hole will interfere, to a degree, with mixing and proper catylization of polyester resin. Further, pullout strengths are degraded in typical depth anchors (15-in. embedment) in concrete. The question still remained, however, as to whether the integrity of bolts installed in wet field conditions should be suspect.

43. The main difference between the laboratory tests on concrete anchors and rock bolt applications in the field is the length of hole utilized. Very few, if any, rockbolts are installed in holes drilled only 15 in. deep. More understanding of the problem was needed to make a technically sound recommendation on the use of polyester resin grout in submerged, geotechnical applications.

WES Laboratory Study

44. A brief test series was run in March 1987 at the Geotechnical Laboratory of WES to provide a cursory evaluation of the resin mixing phenomenon. They were intended only to lend insight to the interaction between water and resin during the installation process. The main purpose, therefore, was to reduce the number of variables to those that have the greatest influence on the resin's performance. Further detailed studies could then be conducted on the major variables to determine quantitative effects on bolt performance.

45. The tests consisted of installing 3-ft long, No. 6 Dywidag bolts into 1-in. diam PVC tubes that were capped on one end. One end of the bolt was turned down on a lathe to permit it to be chucked into a 3/8-in. variable speed drill. Celtite fast-set resin cartridges were placed into either dry or water filled tubes and the bolt was spun into the resin. The bolt was pushed with the drill by hand as hard as possible into the resin. The drill was running at about 200 rpm. Between 10 and 15 sec was required to push the bolt to the bottom of the tube. The bolt was then spun for an additional 15 sec. After the resin had hardened, the PVC tubes were slit open and the resin was examined.

Dry control test, one cartridge

46. The first mix test utilized one resin cartridge in a dry tube. During bolt installation, the tube became very warm to the touch. After waiting approximately 10 min, well beyond the manufacturers suggested minimum curing time, the PVC tube was cut open. The resulting grout column is shown in Figure 1. The resin column was a consistent black color. There were some areas along the grout length where air bubbles were entrained in the resin. None of the air bubbles exposed an uncoated portion of the bolt. From physical inspections, the resin coating on the bar was hard and well adhered.

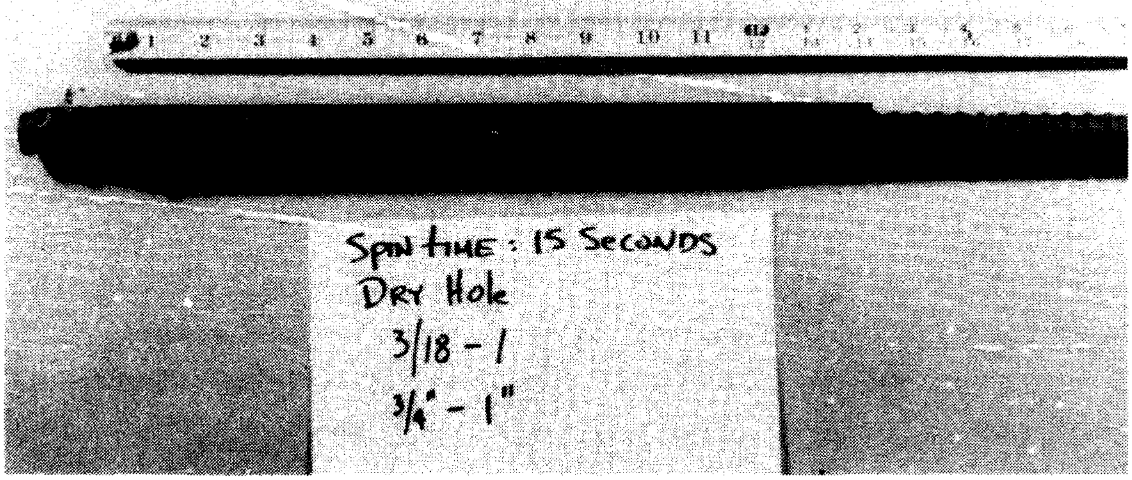

Figure 1. WES Single Cartridge Mix Test, Dry

Wet control test, one cartridge

47. Another installation was conducted with one cartridge of resin installed in a water-filled PVC tube. This installation produced some temperature rise, but not to the degree of the dry installed bolt. Also, the grout did not firm up as the dry installation did. After the waiting period, when the tube was cut open, a gooey resin-water emulsion remained in the tube. There were some portions on the lower end of the bolt where the resin appeared to set properly (Figure 2). Some of these portions were porous and easily scraped off the bar. In Figure 3, voids can be seen between the deformations of the bar where water was entrained during mixing. Toward the lower end of the bar, the resin was a^tually quite hard and not as easily scraped off the bar. The overall appearance of the bar and grout was similar to the description of the resin on the bolts pulled from the Monongahela Lock and Dam 3 lock rehabilitation work.

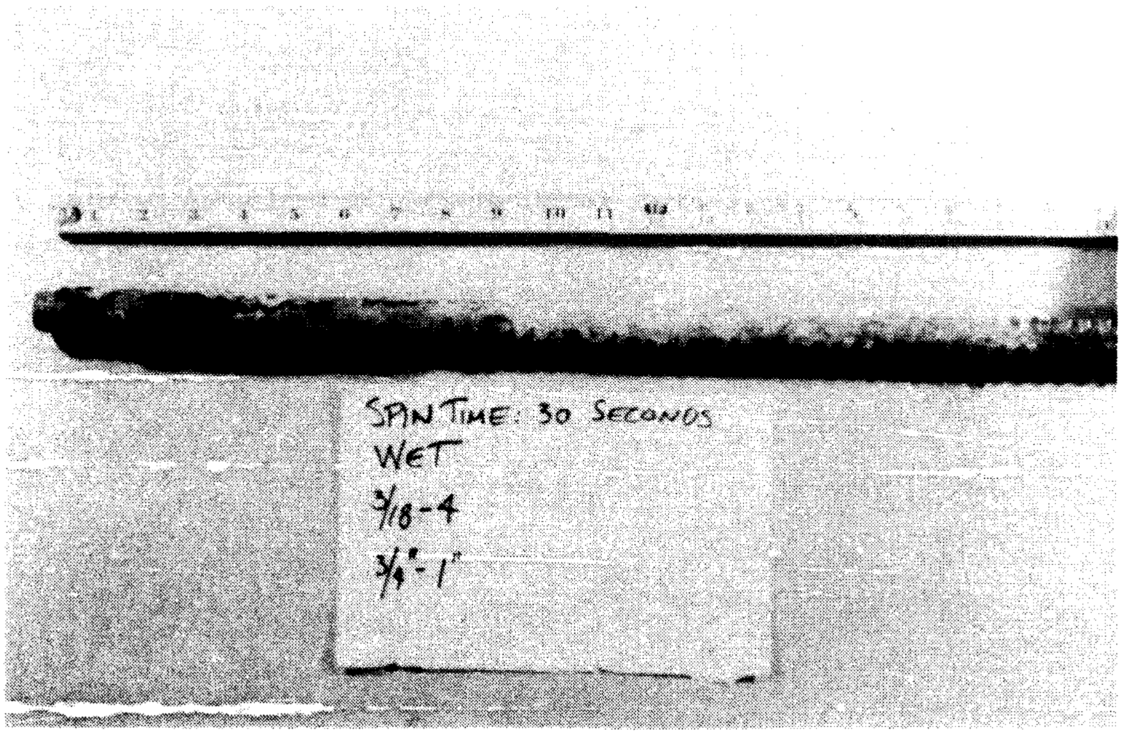

Figure 2. WES single cartridge mix test, wet

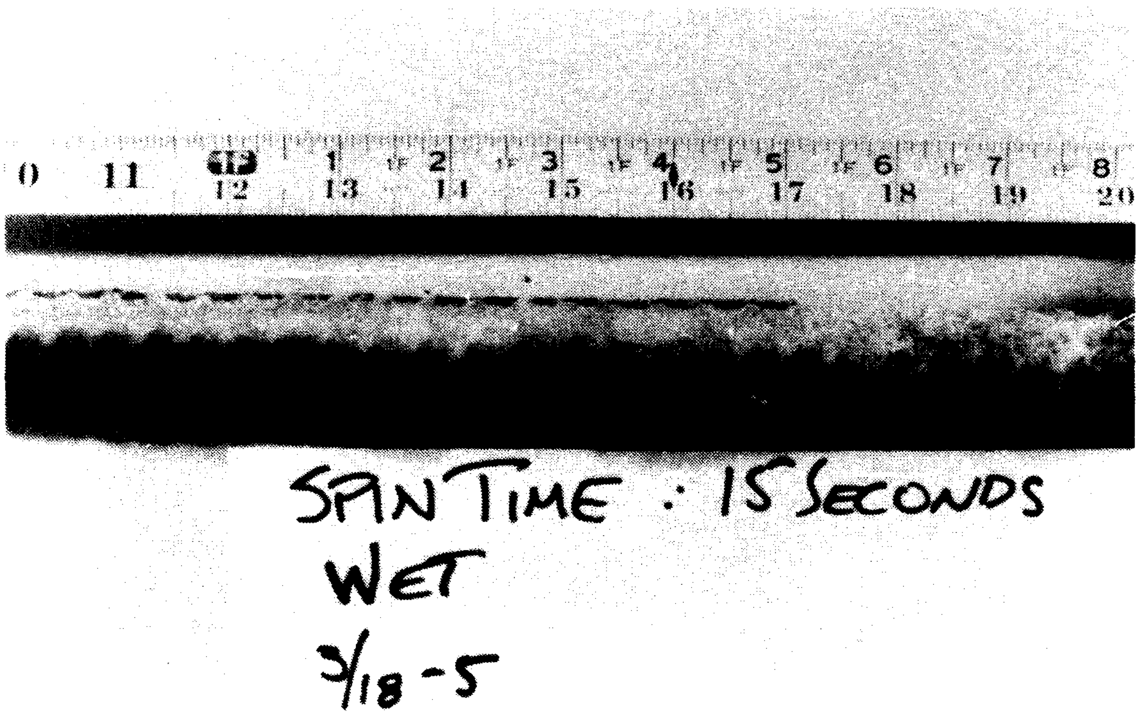

Figure 3. Voids in resin due to water entrainment

Wet test, two cartridges

48. The final test installation was conducted with two cartridges of resin in a water-filled hole. A significant heat rise, similar to that produced in the dry installation test was felt. After the waiting period, the tube was cut open revealing several variations in resin hardness. The top portion of resin was still soft and runny, similar to the single cartridge wet installation. The remaining resin was hard, as shown in Figure 4. The lower 18 in. was more representative of the dry installation, being hard and dense, as shown in Figure 5. The lower portion was gray, but was not easily scraped from the bar. The top 3 to 4 in. of the resin column was easily scraped from the bar and more porous than the lower section.

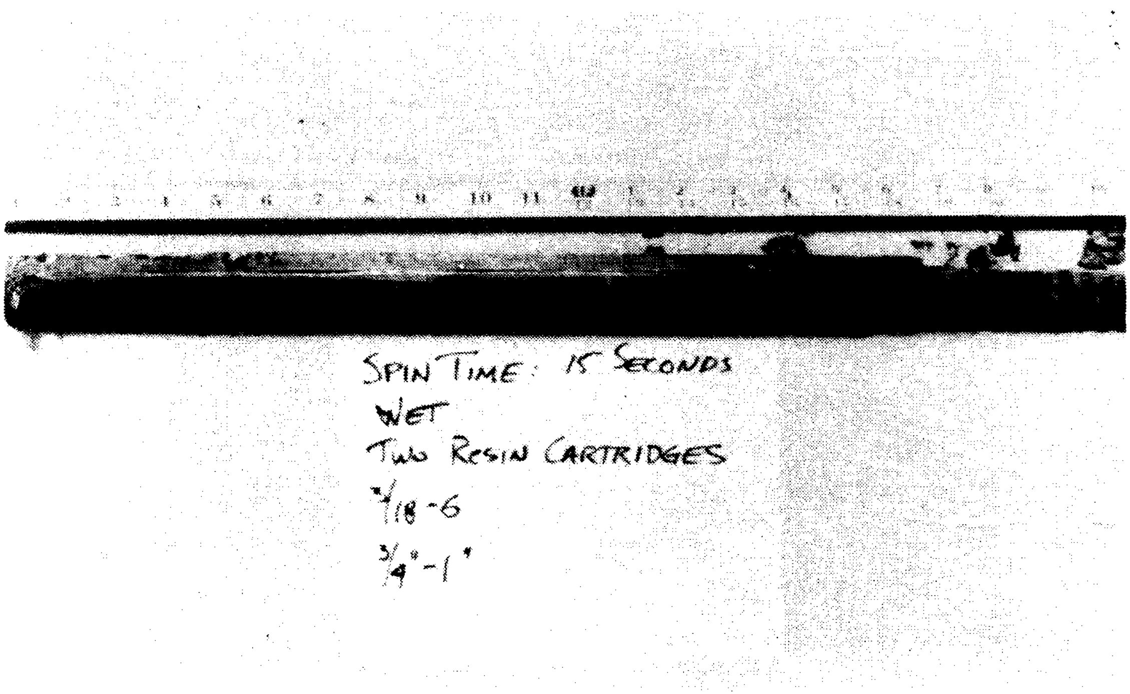

Figure 4. WES two-cartridge, wet test

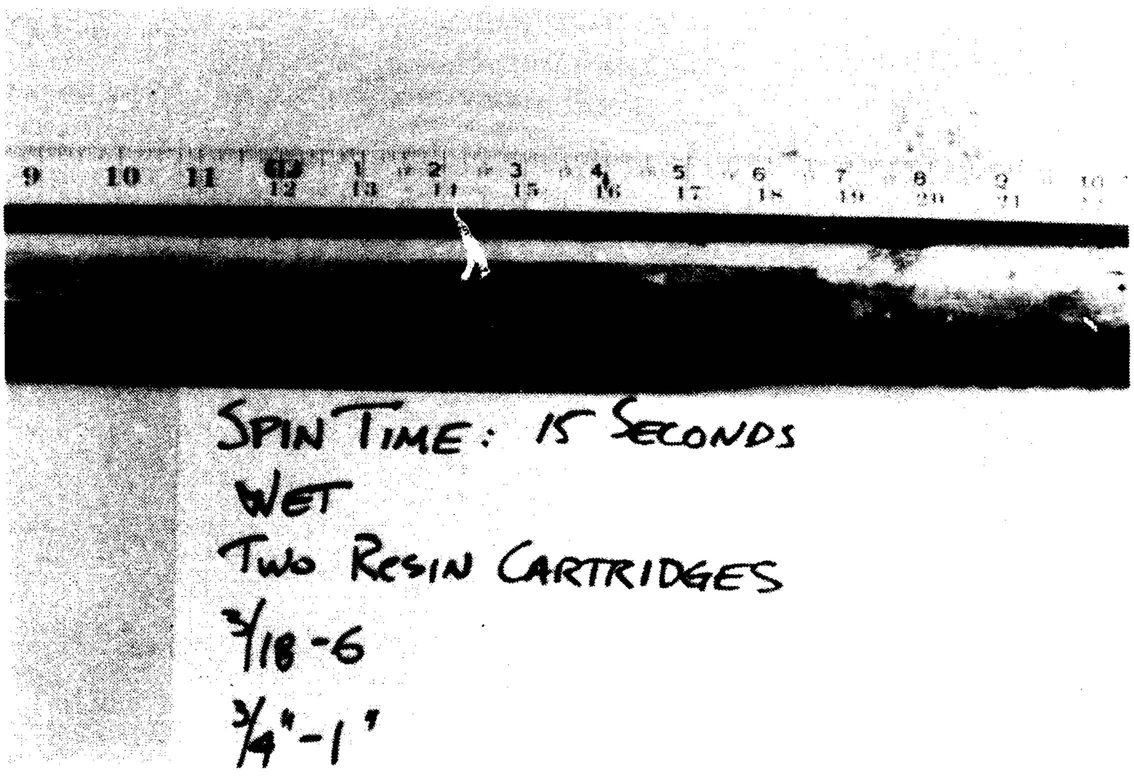

Figure 5. WES two-cartridge test, lower portion

Summary

49. The simple tests conducted in PVC tubes revealed important clues into the interaction between water and resin. The blending of resin and water took place in the top 12 to 14 in. of the resin column, regardless of whether one or two cartridges of resin were used. The near total dilution of the top 12 in. of resin helps to explain the poor performance of the 15-in. Singleton tests of resin bolts installed under submerged conditions.

50. Analyzing and observing the mechanisms of bolt installation aided in the explanation of why the top 1 ft of the resin column fails to set up properly. The resin cartridges are quite tough and do not puncture without sufficient force being applied to them. Prior to puncturing the resin cartridge, the bolt pushes it into the bottom of the hole, expelling water from the space between the cartridge and borehole wall as it deforms. The cartridge bursts after the spinning bolt has compacted it into the hole. The resin is now blended with the water, primarily in the top portion of the borehole at the water-resin interface. The thread-like deformations on the spinning bolt act to pump water into the resin column. The high viscosity of the resin restricts the penetration of water to 12 to 14 in. during the 15-sec spin time.

51. Significant variables in obtaining a proper resin anchor identified by these tests include:

a. The depth of the hole.

b. The number of cartridges used.

c. The spin time.

These initial tests provided excellent visual data of the interaction between water and resin, but did not provide any information regarding the strength characteristics of the resin grout. From these results, further tests were planned by WES and conducted at the Bureau of Mines, Denver Research Center. The tests were designed to quantitatively assess the performance of a polyester resin grouted bolt when water is present during installation.

Bureau of Mines, Denver Research Center Tests

52. During the period April through October 1987, The Denver Research Center, sponsored by the Corps of Engineers, undertook a series of tests to investigate the use of polyester resin as an anchoring grout in submerged rockbolt installations. This effort was reported in an unpublished document

by Cherrier and Lutzens (1988). This section is a synopsis of their work.

53. The objective of these tests was to determine the effects that water in the borehole has upon the overall strength of the polyester resin rockbolt system. The TVA tests had shown a considerable effect on pull strength and creep but were limited to 15-in. lengths in concrete. The brief mixing tests conducted at WES indicated that only the last 12 to 14 in. of resin was adversely affected by the water. These tests also indicated that, in longer bolts, there may be adequate mixing of the resin at further distances from the resin-water interface to achieve design anchoring loads. The desired tests, therefore, were to include 1-, 2-, and 3-ft long holes in order to establish the effect of hole length. Dry and damp holes were desired for control tests.

Test conditions

54. Test media. All tests were conducted in concrete blocks approximately 1 yd^3. Figure 6 shows the overall test matrix. The number and size of the blocks, type of resin, depth of the drilled holes, length of bolt, and desired water influence are all depicted.

55. A sand and cement concrete mixture without aggregate was specified to obtain uniformity. An 8.4 sack per cu yd mix with a 4- to 4.5-in. slump was specified. This mix was designed to provide a 4,000-psi minimum compressive strength concrete in 28 days. The blocks were formed, poured, and vibrated in two groups of six to accommodate a full truck load of concrete and to allow reuse of the forms. All blocks were properly cured for 28 days, after which a sample concrete cylinder was cored and tested. The test specimen met the 4,000-psi minimum requirement.

56. Drill holes. The bolt pattern selected for each block allowed five holes, with about 10.5 in. between holes or between the hole and the outer block surface. This was judged to be an adequate distance between bolts to avoid any interference with the pull test effect upon the data obtained.

57. A Sprague and Henwood C40 drill with a masonry diamond core drill bit having a nominal 1-in. outside diameter (OD) was used to drill the holes. Previous research by the Mining Enforcement and Safety Administration indicated that a nominal 1-in. hole diam should be used with nominal 3/4-in. diam

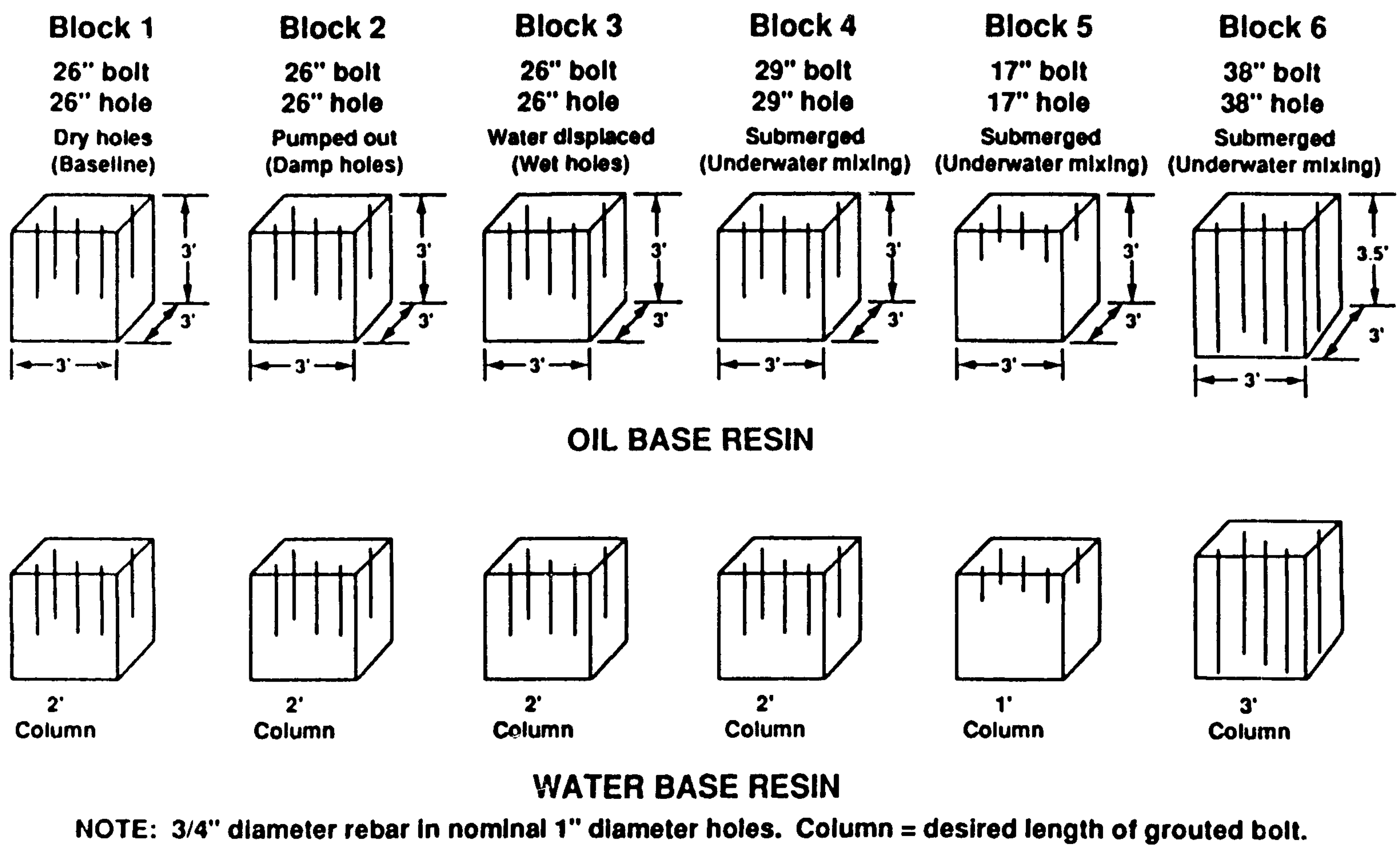

Figure 6. Rockbolt Pull Test Matrix

bolts to provide the most effective resin grouted bolt installation (Karabin and Debevec 1976). Since the bit and core barrel were only 17-in. long, a 1-ft extension rod was used as necessary for the deeper holes. The pattern and the drill hole numbering system are shown in Figure 7.

58. The bolt lengths shown in Figure 6 are measured from the bottom side of the bolt head flange to the end of the bolt. A 1-in. pull collar was placed on every bolt and was flush against the bottom of the flange. Thus, a bolt having the same length as the hole depth will theoretically be 1 in. off the bottom of the hole. This method was used to ensure that there would always be a slight gap at the bottom of the hole when slightly oversize bolts went into slightly shorter holes.

59. Except for the holes in the two blocks intended for dry control tests, all holes were filled with water after drilling and kept full for a minimum of 2 weeks or until the bolts were installed. This was done to ensure that the block was saturated and to duplicate as nearly as possible underwater conditions.

60. The boreholes were drilled using a diamond core drill. This is contrary to recommended practice because of the smooth finish inner diameter created. A rotary-percussive drill is preferred. This change from standard practice, however, did not affect the comparative validity of the tests.

61. Rockbolts. No. 6 headed rebar, grade 60 steel bolts, with a minimum load capacity of approximately 26,000 lb, were ordered from Pattin Manufacturing Company in Marion, Illinois. This high strength bolt was used to ensure that, if failure occurred, it would be in the grout and not in the bolt itself. The nominal bolt diam was 0.75 in. Figure 8 shows a typical block with four of the five bolts installed.

62. Resin. "FASLOC-T" and "FASLOC I.D." polyester resins were used for the pull out strength tests. Both of these are manufactured by E.I. DuPont de Nemours & Co., Inc. The "FASLOC-T" oil base resin was ordered with a 2-min gel time. Cartridge dimensions were 0.9-in. diam by 17 in. long. The "FASLOC I.D." water base resin, System A-2, was also ordered with a 2-min gel time and had cartridge dimensions of 0.9-in. diam by 12 in. long.

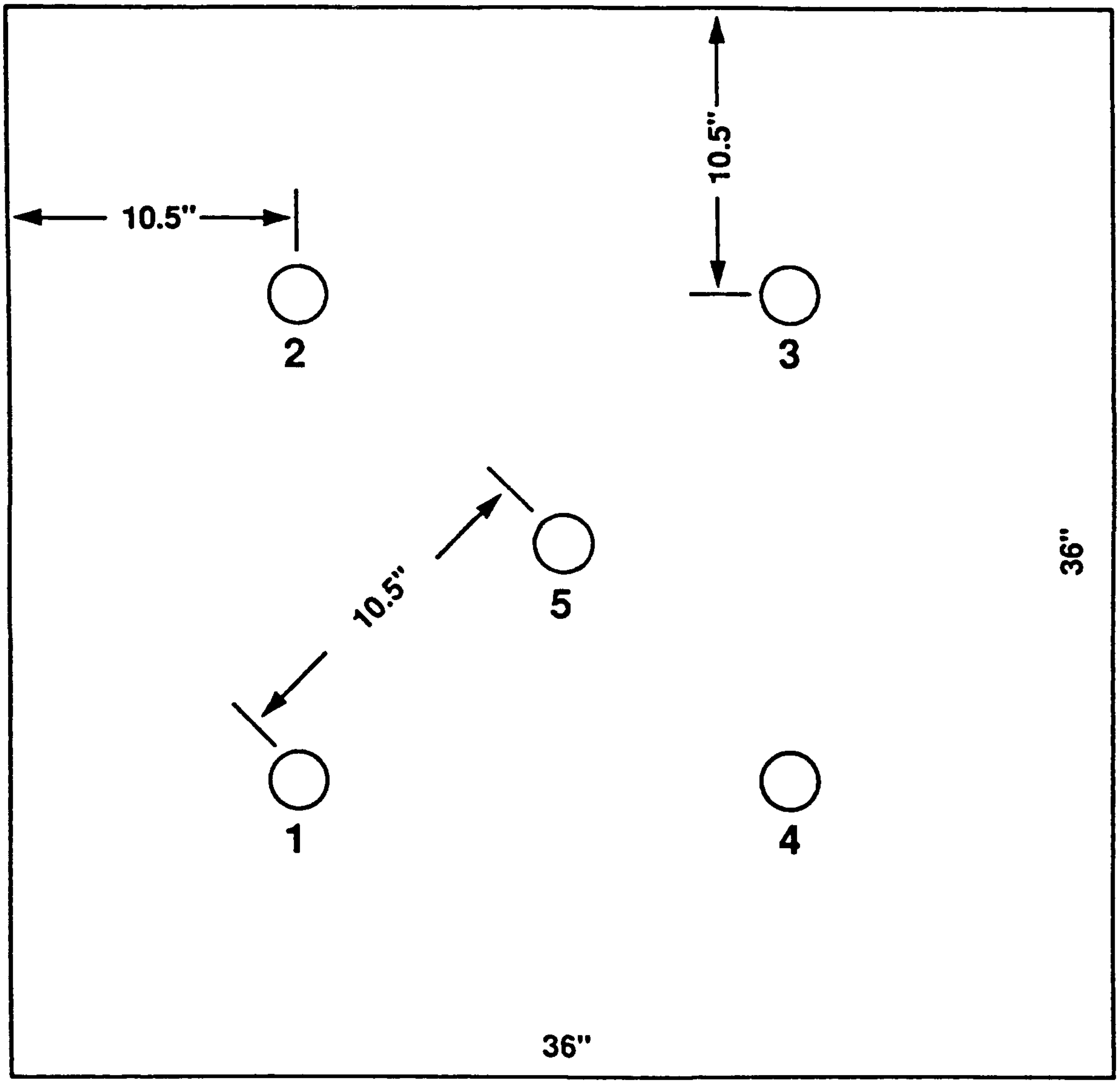

Figure 7. Schematic of a typical block pattern

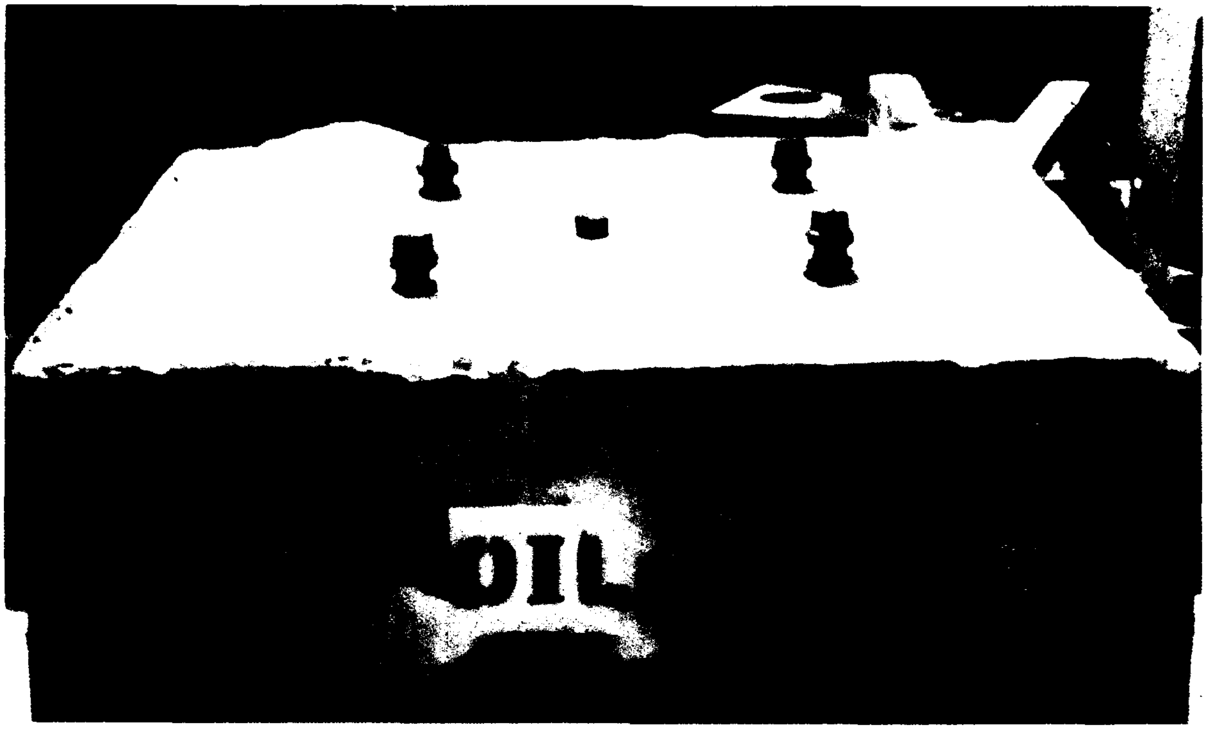

Figure 8. Typical block, four of five bolts installed

Installation procedures

63. Installation and pull testing were planned to follow the sequence of block No. 1 through block No. 6, shown in Figure 1, thus the dry bolts installed were tested first followed by the damp, wet, and submerged installations. Typically, one block using oil base resin and the corresponding block using water base resin had bolts installed at the same time. The bolts were allowed to cure to 20 hr and were pull tested the next day. This provided a consistent curing process and assured that tests were directly comparable.

64. The first three blocks for each resin type were planned to utilize sufficient resin to provide at least 2 ft of grouted bolt length. The resin cartridges were cut when necessary to provide the correct grout column length. This length varied because of the interaction of bolt length, hole depth, and hole diameter. Block No. 1 for both resins was also a trial to establish the desired grout quantities necessary for the intended column lengths. In fact, all installation results were used to make minor adjustments in resin volume for subsequent holes.

65. The selected length of grout cartridge was dropped into the hole and the bolt was inserted until it rested on the grout cartridge. A Turmag drill and chuck were put on top of the bolt and forced downward to insert the bolt fully into the hole. The Turmag drill is a hand-held, air-driven, variable speed rotary drill, well suited for bolt installation. Figure 9 shows a typical installation process with the grout cartridge about to be dropped into the hole, and the rockbolt and drill at the ready.

66. The resin manufacturer's specifications for installing bolts in both types of resin were to insert the bolt to the bottom of the hole and spin the bolt at between 350 and 600 rpm. Slow spinning of the bolt to assist in bolt insertion was an option suggested by the manufacturer. After spinning to mix the resin and catalyst, the bolt was held in place for a short time while curing took place.

Pull test procedures

67. A standard hydraulic rockbolt pull test apparatus was used to provide loads in 1,000-lb increments up to 30,000-lb total. Figure 10 shows the hydraulic ram and pulling claw which attach to the bolt. The pulling collar can be seen directly beneath the bolt head. The hydraulic ram was activated with a standard hand-operated pump. A pressure gage, calibrated to read in pounds-force, permitted application of the force in the desired increments. An extensometer with a calibrated gage reading in 0.001-in. increments was mounted between the arm on the pull head and the surface of the block. Figure 11 shows the apparatus being readied for use. The extensometer measured the elongation of both the bolt and the pull apparatus as force was increased. Elongation was read to the nearest 0.0005 in.

68. Additional displacement readings were obtained using a recently developed USBM ultrasonic measurement system. This technique utilizes the standard pulling apparatus but measures elongation in the bolt only by using a sending and receiving transducer mounted on the head of the bolt. Both ends of the bolt must be machined to a very flat, smooth surface perpendicular to the longitudinal axis of the bolt. An electrical pulse is sent to the transducer which converts this pulse to a mechanical pulse. The pulse travels through the bolt at the speed of sound, is reflected by the end of the bolt, and is detected when it returns to the transducer. The system requires the

Figure 9. Installation process

Figure 10. Bolt pull test apparatus ready for attachment

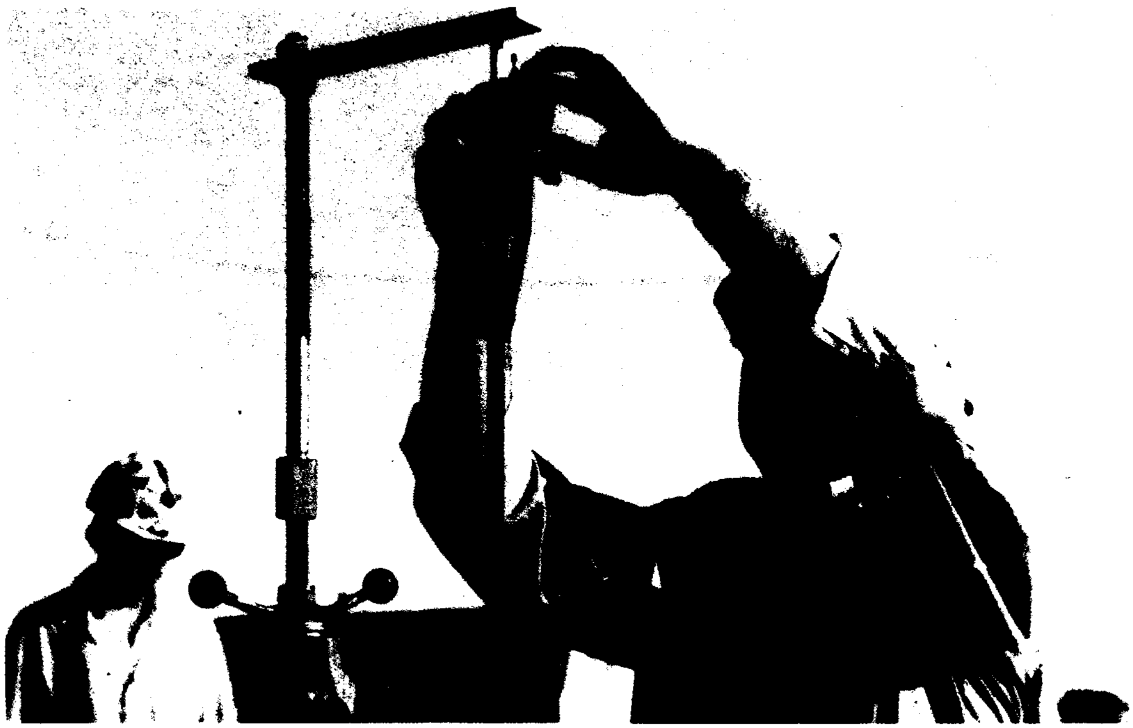

Figure 11. Extensometer being prepared for pull test

bolt metal characteristics as input and corrects the signal time for a variety of factors including stress level, temperature, and signal amplitude variation. Displacement readings are automatically produced in 0.0001-in. increments on a digital readout. This equipment was used on the center hole (No. 5) on all blocks except the two short hole (17-in.) blocks. The 17-in. holes were considered too short for effective use.

Pull test results

69. All the recorded and computed data derived from the pull tests are contained in the tables of Appendix A. Further, Appendix A contains plots of load versus displacement for all tests.

70. Minor problems were experienced with seating the puller properly on top of the block. This was due to an irregular block surface resulting in the bolt head bottom surface not being exactly parallel to the surface of the block. Even with a soft aluminum plate between the puller and the concrete surface, some unusual readings occurred. These difficulties did not significantly affect the test results, as in all but one case (hole No. 2, oil block No. 2), the effect occurred in the initial load range up to 10,000 lb. Thereafter, this test plot showed similar characteristics as the other curves on the graph. In most cases, the larger initial positive or negative readings

simply moved the curve right or left on the graph but maintained nearly the same slope and about the same relative displacement after adjusting for the initial seating. The most noticeable examples of pull test curve distortion are hole 3 in oil block No. 4, hole 1 in oil block No. 6, and hole No. 4 in water block No. 1. Hole 5 in oil block No. 4 suffered a data loss after 26,000 lb of load but appeared to be holding as well as the other bolts.

71. In spite of these minor distortions, the objective to determine if grout failure would occur as a result of wet installation was accomplished. The graphs show that, when two or more column feet of grout are used, failure would not be expected. Bolts held up to 30,000 lb of load. Since both block No. 1's were dry and both block No. 2's were damp, only block No. 3 and block No. 4 could be used to assess wet conditions with two column feet of both types of resin. Only one failure of the grout occurred out of 20 completely wet tests. This occurred in hole 4 of oil block No. 3, as shown in Figure 12.

72. A jackhammer was used to remove the front of selected blocks for observation. In some cases, this action appeared to dislodge pieces of possibly weaker grout columns. Figure 13 shows the exposed front of oil block No. 3 and the displacement of the bolt in hole 4. Hole 1 shows a completely full grout column in the upper portion while hole 4 shows no grout near the collar. Figure 14 is a closeup photo of the lower portion of hole 4. "Glove fingering" of the grout tube is apparent. This likely prevented the grout from bonding properly. "Glove fingering" occurs when the bolt spins inside the plastic grout tube skin, leaving it relatively intact, which prevents the grout from setting up securely against the hole wall.

73. The graphs for the two block No. 6's show no failures using three column feet of grout. There might be a hint that something different happened in the water-based resin grout because of the generally greater elongation. This is very likely due to slightly less grout in the water-based holes which left a portion of the top of the bolt ungrouted. During the pull test, added elongation could occur in this ungrouted portion.

<u>Summary of results</u>

74. <u>Water-based versus oil-based resin grout</u>. Only in very short grout lengths (1 ft) and in submerged installations was any difference in holding

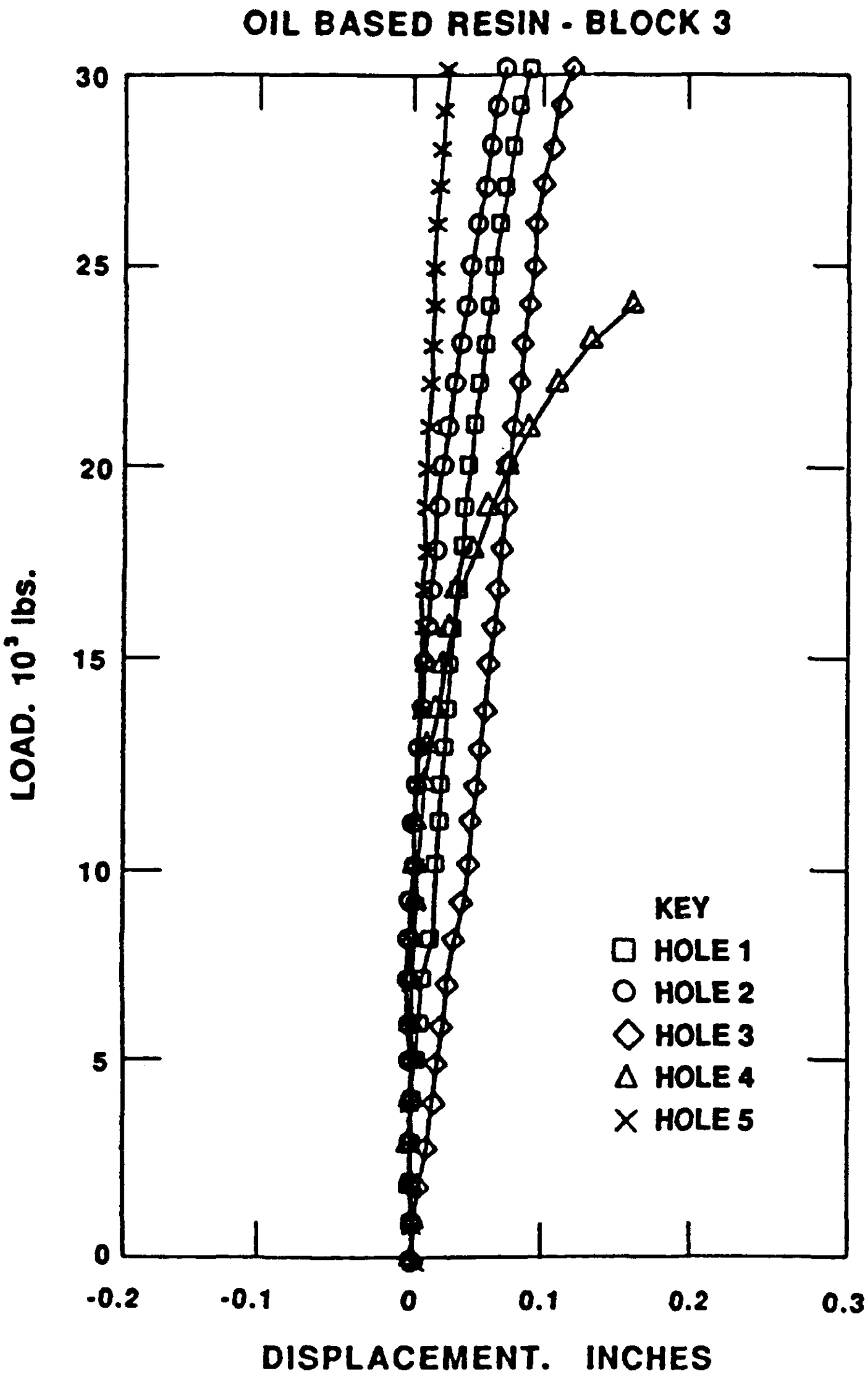

Figure 12. Block No. 3, oil-based resin, displacement versus load

Figure 13. Split block No. 3 showing holes 1 and 4, left and right

Figure 14. Close-up of block No. 3, hole 4

power of the two resin types detected. The water-based resin provided significantly greater strength in all short hole tests. No difference was detected when using 2- or 3-column ft of grout, nor when used in dry holes.

75. Improper shredding of the resin cartridge. Only one failure occurred in all the pull tests of holes greater than 2 ft. This was caused by a phenomenon known as "glove fingering." In this situation the cartridge case does not get shredded into the resin but forms a barrier against the borehole wall and prevents normal interlocking. This situation may have been exaggerated in this case because the hole was drilled with a diamond drill and had an undesirably smooth inner surface. This situation would not be serious in longer holes, and, as a preventative measure, some brands of bolts contain "wings" on the ends to aid in cartridge shredding.

76. Dry versus wet installation in grout columns over 2 ft long. The dry baseline two foot grout column tests did not exhibit any better strength characteristics than wet installations. While it is true that bolts from both types of installations held to the required strength, bolts from both types of installations were not tested to failure.

77. Holding strength. The two or three column foot grouted bolts demonstrated the ability to hold up to the yield strength of the bolt, about 30,000 lb. This indicates a unit strength of over 1,200 lb per grouted in. In the short holes, water-based resin held from 1,500- to 2,500-lb per grouted in., and oil-based resin held from 200- to 1,000-lb per grouted in.

78. Conclusion. Based on the test data generated, a water-based polyester resin should be considered for shorter, wet condition holes within the strength ranges demonstrated. Either resin base is probably acceptable in the presence of water when longer grout columns are used. Proper attention must be paid to installation procedures and hole annulus size. Holes should be drilled with R-P units to achieve a rough inner diameter, and precautions to avoid "glove fingering" should be taken, especially if holes are short.

79. This study determined that a submerged installation did have some deleterious effect on resin catylization and/or polymerization. The exact phenomenon was not determined. Any dire consequences in construction projects can be avoided by the use of longer holes and longer grout columns.

Bonneville Lock and Dam Project

Project Background

80. In 1987, the Corps of Engineers awarded a contract for the construction of a major new lock facility at the Bonneville Lock and Dam project.

81. The Bonneville project is located on the Columbia River at the head of tidewater, 146 miles above the river mouth, and 42 miles east of Portland, Oregon. Figure 15 is a general layout map of the Bonneville area with an inset vicinity map showing the location of the project.

82. The Oregon-Washington state boundary follows the main Columbia River channel, dividing the project between the two states. The northern half of the spillway dam, Cascades Island fish facilities, and the Second Powerhouse are located on the Washington side of the river. The south half of the spillway dam, the First Powerhouse, Bradford Island fish facilities, the existing navigation lock, and the new navigation lock site are in Oregon.

83. The project plan included extensive use of resin grouted rockbolts, incorporated to anchor the new construction to the rock.

84. The contract was awarded to Guy F. Atkinson Co., and, for the cooperation and support received during this test program, public acknowledgement and appreciation are given.

Geology

85. The stratigraphic sequence of overburden and rock layers in the Bonneville area is a result of lava flows overlying sedimentary rock layers which are locally intruded by igneous rock and buried by landslide and alluvial deposits.

86. The oldest rock unit in the Bonneville area is the Weigle Formation. It underlies most of the valley floor but is buried by landslide and alluvial deposits. The formation consists of interbeds of claystone, sandstone, and conglomerates which dip less than 30 deg toward the Oregon shore. The Eagle Creek Formation unconformably overlies the Weigle Formation. It is exposed in the highway cuts along Interstate 84 on the Oregon shore and also at higher elevations on the gorge walls above the landslide and talus debris. The Eagle Creek Formation is composed primarily of volcanic conglomerates or agglomerates that contain both rounded and angular fragments. The Eagle Creek Formation is overlain by the Columbia River Basalt Flows which form near vertical cliffs in the gorge. The Rhododendron Formation, which

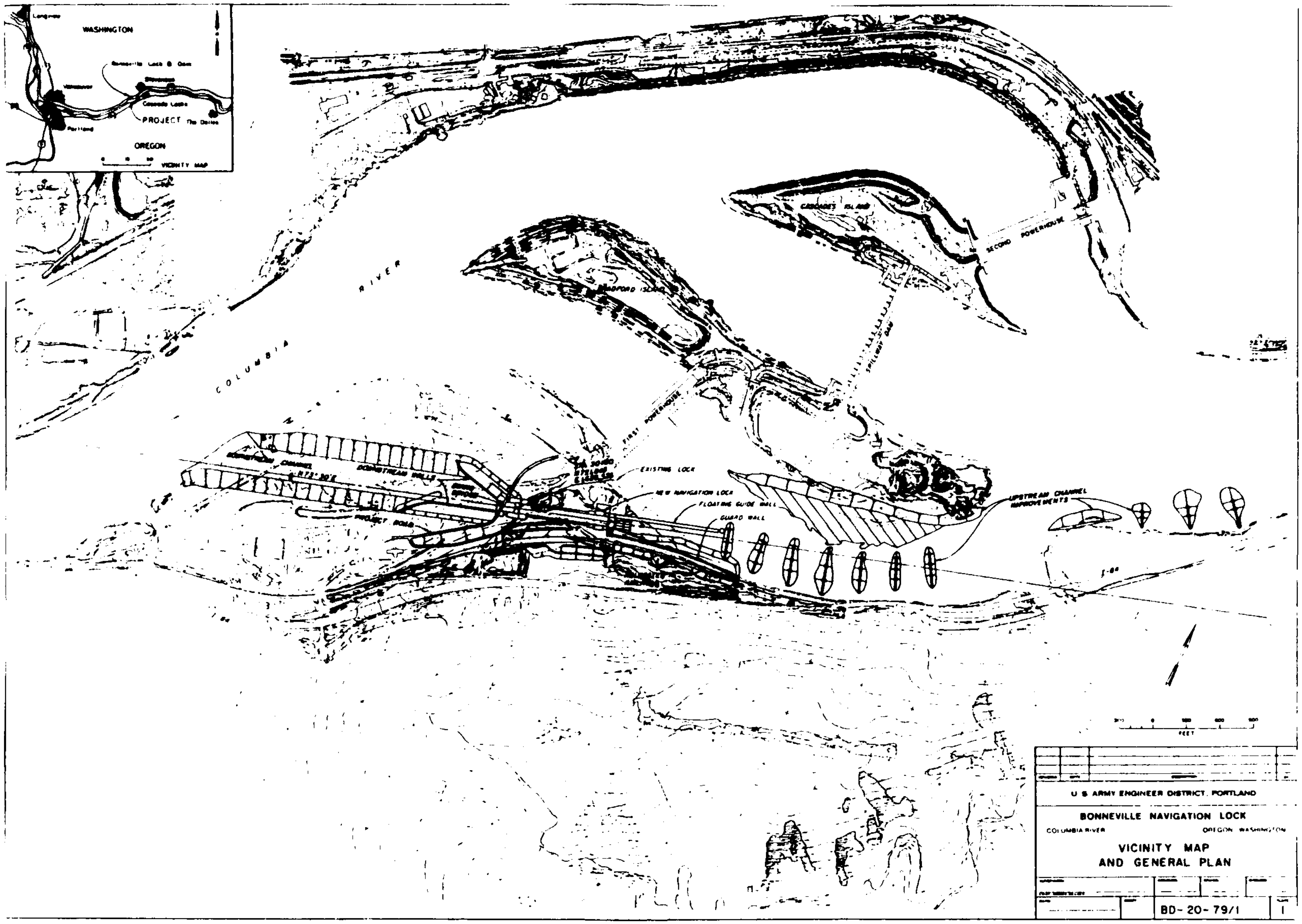

Figure 15. Bonneville navigation lock, map, and plan

consists of ash, tuffs, and volcanic conglomerates or agglomerates, overlies the basalt flows in eroded channel areas near the top of the gorge walls. The youngest rocks at the site are the Olivine Basalt Flows. These rocks overlie the Rhododendron Formation and form the ridges near the top of the gorge. Intrusive rocks of similar composition and age form the Bonney Rock, a rock knob just south of the existing navigation lock on the Oregon shore. It is a highly columnar-jointed, irregular-shaped sill of diabase that appears to have intruded both the Weigle and Eagle Creek Formations.

87. The alignment and positioning of the new lock are designed to take full advantage of the narrow resistant rock ridge of Bonney Rock. This is the same rock mass in which the existing lock chamber and the southern foundation of the powerhouse are founded. Bonney Rock falls below lock grade beyond the ends of the proposed lock chamber. All rockbolt installations and testing were conducted in Bonney Rock. Figure 16 is a detailed drawing of the rockbolt test area.

Test matrix

88. During October and November 1987, a total of 84 tests were conducted in the Bonney Rock Formation, arranged in eight test series. Variables included:

a. Depth of hole.
b. Diameter of hole, ie., clearance between bolt and hole.
c. Submerged (wet) or dry installation.
d. Grout length.

One unplanned variable was also encountered during testing, cleanliness of the hole. A special test series was run to identify this variable.

89. Constants maintained throughout the tests included:

a. The type of drill, Ingersoll-Rand ECM 350.
b. The bolt diameter, No. 11 (1-3/8-in. diam).
c. The brand of bolt, Dywidag.
d. Installation procedure, with minor exceptions noted.
e. Resin type, Celtite.
f. A near-horizontal hole orientation.

Table 2 lists all the tests in each series along with the major variables of each. The following paragraphs briefly describe the intent and features of each test series.

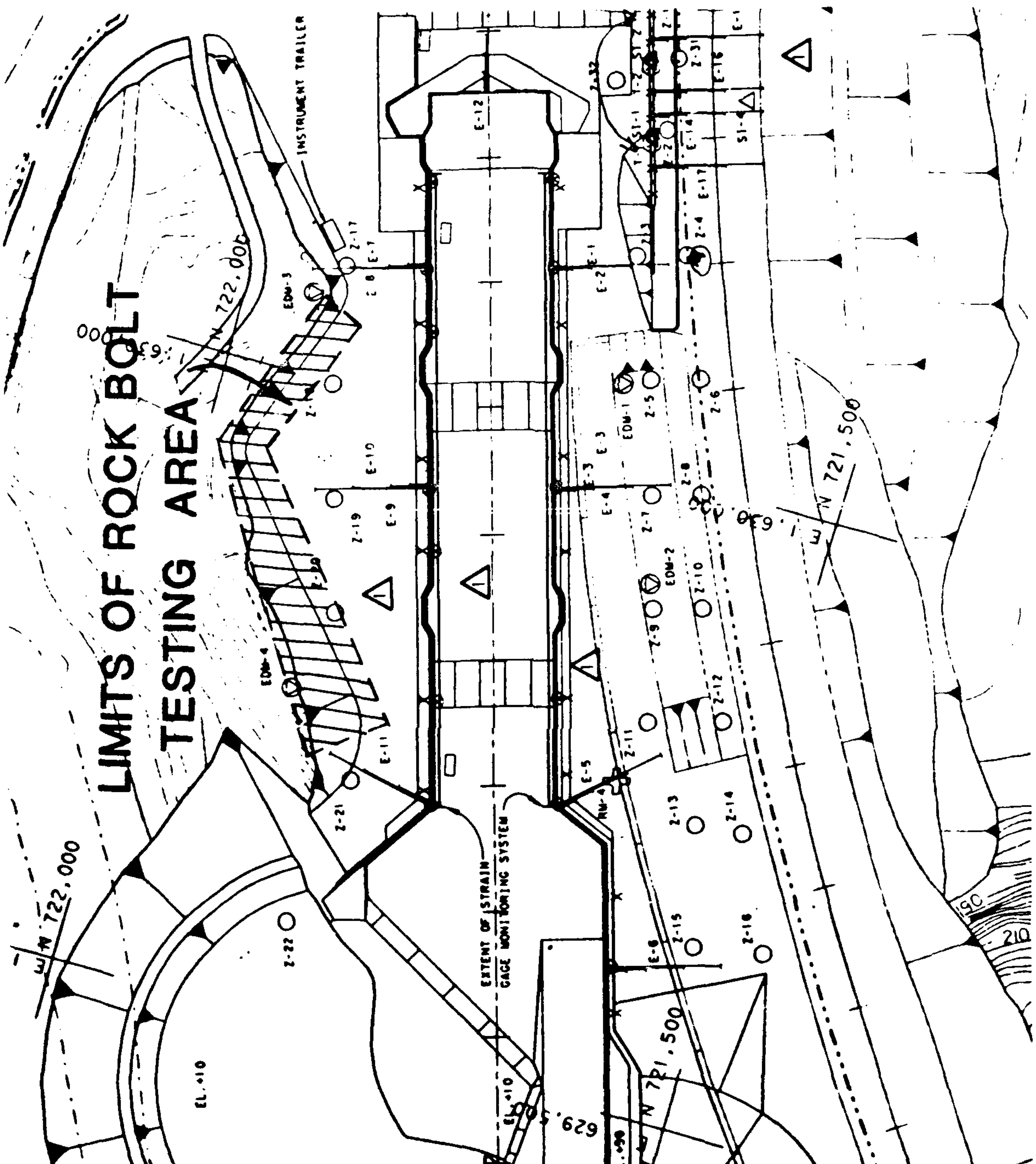

Figure 16. Bonneville rockbolt test area

Table 2

Bonneville Locks, Rockbolt Test Matrix

Series	Tests	Hole Depth ft	Hole Diameter in.	Condition	Grout Llength in.
1	1-12	8	2-1/4	dry	24-96
2	1-10	8	2-1/4	wet	24-96
2	11-12	8	2-1/4	wet	96
3	1- 3	5	2-1/4	dry	26-28
3	4- 6	5	2-1/8	dry	28.5-32
3	7- 9	5	2	dry	23-36
3	10-12	8	2-1/4	dry	26.5-35
3	13-15	8	2-1/8	dry	47-51
3	16-18	8	2	dry	53
4	1- 3	5	2-1/4	wet	26-31
4	4- 6	5	2-1/8	wet	29.5-33
4	7- 9	5	2	wet	36
4	10-12	8	2-1/4	wet	26.5-41
4	13-15	8	2-1/8	wet	47-51
4	16-18	8	2	wet	53
L	1- 4	8	2-1/8	damp(clean)	48
B	1- 4	8	2-1/2	damp(clean)	48
T	1- 4	8	2-1/8	dry	24-44.5
T	5- 8	8	2-1/4	dry	50.5-84
S	1- 4	18	2-1/8	dry	120
S	4- 8	18	2-1/4	dry	120

90. Test Series 1. This test series was conducted to determine a baseline strength for dry installed bolts. The hole diameter was 2-1/4 in. and was drilled to a depth of 8 ft. Grouted lengths were nominally 2-, 4-, 6-, and 8 ft. The anchor was stressed until the resin anchor failed or until the yield strength of the bolt was reached.

91. Test bolts Nos. 1-10, 1-11, 1-12 were installed by pushing the bolt through the resin to the back of the hole and then spinning it for the required time. These bolts had an 8-ft grouted length. All other bolts were spun as they were inserted.

92. Test Series 2. This test series was identical to Test Series 1 except that the bolts were installed in submerged boreholes. The 8-ft grouted bolts in this series were installed using the standard spin and push method.

93. Test Series 3. This test series assessed the pullout strength of anchors installed in different diameter and length dry holes. Hole sizes of 2-, 2-1/8-, and 2-1/4 in. and hole depths of 5 and 8 ft were tested. The grouted length was nominally 24 in. in the 5-ft deep hole, and 48 in. in the 8-ft deep hole. Three bolts were tested per hole size.

94. Test Series 4. This test series was identical to Test Series 3, but was conducted on submerged holes.

95. Test Series L and B. The test results of the first four series indicated that a factor in pull strength of the bolts may be hole cleanliness. Hole diameter and water had little effect on the pullout strength of the anchors. Additional bolts were installed in holes that were cleaned thoroughly with water following drilling. Four 2-1/8-in. diam holes, designated L, and four 2-1/2-in. diam holes, designated B, were drilled to a depth of 8 ft. The anchor length was nominally 4 ft.

96. Test Series T. This test series was conducted in boreholes that intercepted a simulated water-bearing fracture. The rock in the test area was dry, so water was injected into the fracture from an adjacent hole. A 3-in. feeder hole was drilled into the rock and penetrated a known fracture. Of the eight bolts installed, one was installed dry because the injected water did not reach the hole.

97. Test Series S. These tests were conducted on 20-ft long bolts installed in 2-1/8- and 2-1/4-in. diam, 18-ft deep boreholes. This test series had two objectives. The first was to determine the performance of a bolt with a 10-ft anchor length, and the second was to evaluate an alternative loading procedure. The alternative procedure was a method of cycling the load between 50 and 150 kips. An increasing displacement at the low load on successive cycles might indicate poor bolt performance.

98. Creep tests. Short-term creep tests were conducted on three of the bolts from Test Series S, S-1, S-2, and S-3. These bolts had been previously pull tested.

Test procedure

99. Rock drilling. The location for each bolt was marked on the rock. The driller was then given the length and sequence of the holes to be drilled. Holes were drilled as perpendicular to the rock face as possible for intended dry installations and downward at a nominal 10 deg for intended wet installations. All bolt holes were drilled using an Ingersoll-Rand ECM 350

Air Track Drill, shown in Figure 17.

100. Initially, holes were to be drilled using only compressed air to flush the cuttings from the hole. However, the drillers injected a small amount of water down the drill string to reduce dust. This latter flushing method tended to build up a film of mud cake on the hole inner diameter. If the hole were to be a wet installation, it was filled with water using the drill string. Filling and overflowing the hole tended to wash some of the mud cake away.

101. Unfortunately, this phenomenon was not noticed until some unusually low pull strengths were observed, likely accounting for the reason that wet installed pull force, on average, actually exceeded the dry installation units. In Test Series B and L, all holes were flushed and bolts installed wet. Results are more representative of good practice.

102. Resin installation. Once the hole was drilled, the resin cartridges were loaded into the hole. Celtite fast-set, oil-based resin was used, but the type and brand are not significant. Resin cartridges were loaded one at a time and pushed to the back of the hole using a powder pole. A powder pole provided a certain sensitivity which could detect when cartridges would hang up or jam in the hole. Using the bolt to push in cartridges was specifically avoided to prevent a premature rupture.

103. Bolt installation. Either of two types of tool was used to insert the bolt. One was a rectangular box attached to the end of a piece of drill pipe, as shown in Figure 18. The alternate was a coupling welded onto a short piece of drill steel. The sides of the couplings were drilled and tapped so that bolts could be screwed in, functioning as set screws to secure the rockbolt. Of the two methods, the rectangular box proved to be more convenient.

104. During installation, the bolts used in the coupling could work loose and release the rockbolt. Several minutes could elapse while reattaching it. During this time, fast-set resin would have hardened and proper rockbolt installation made impossible.

105. All bolts (except for three in Series 1) were installed by spinning as insertion took place and, after bottoming, continuing to spin for about 15 to 20 sec at 200 rpm.

106. Rock face treatment. After installation was complete, but before pull testing, the rock face in the immediate vicinity of the bolt had to be

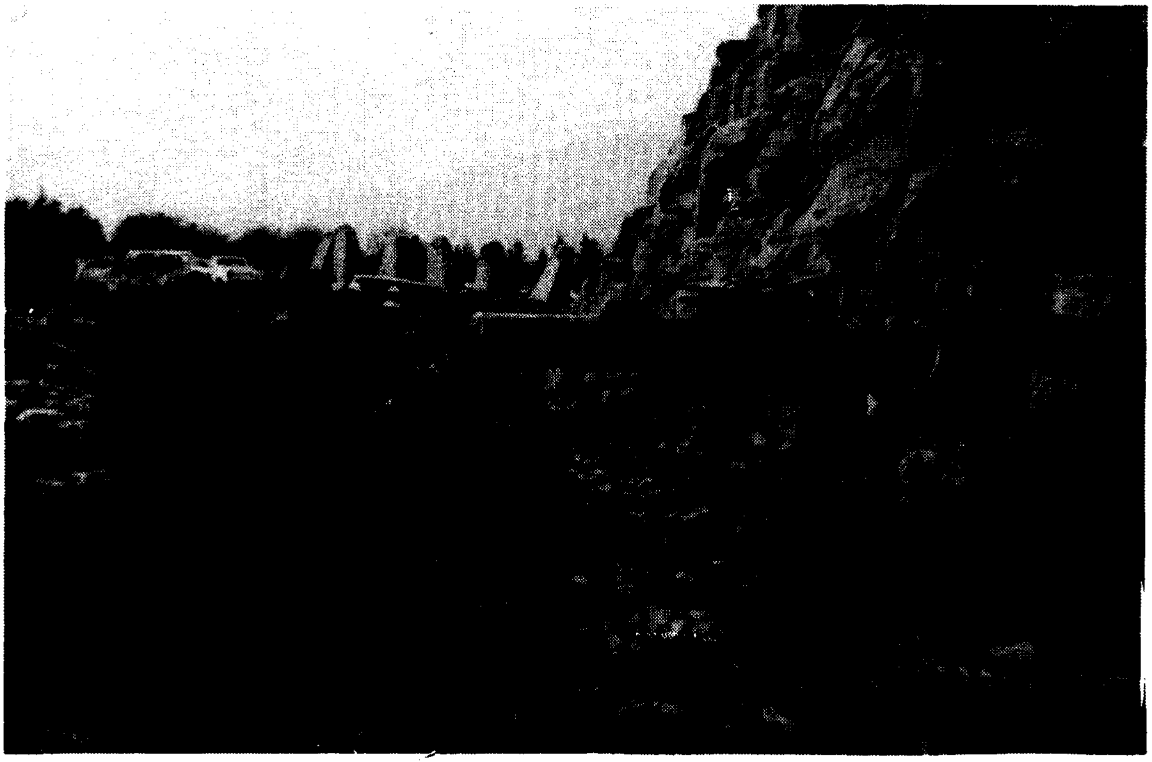

Figure 17. Ingersoll-Rand EMC 350 Air Track Drill

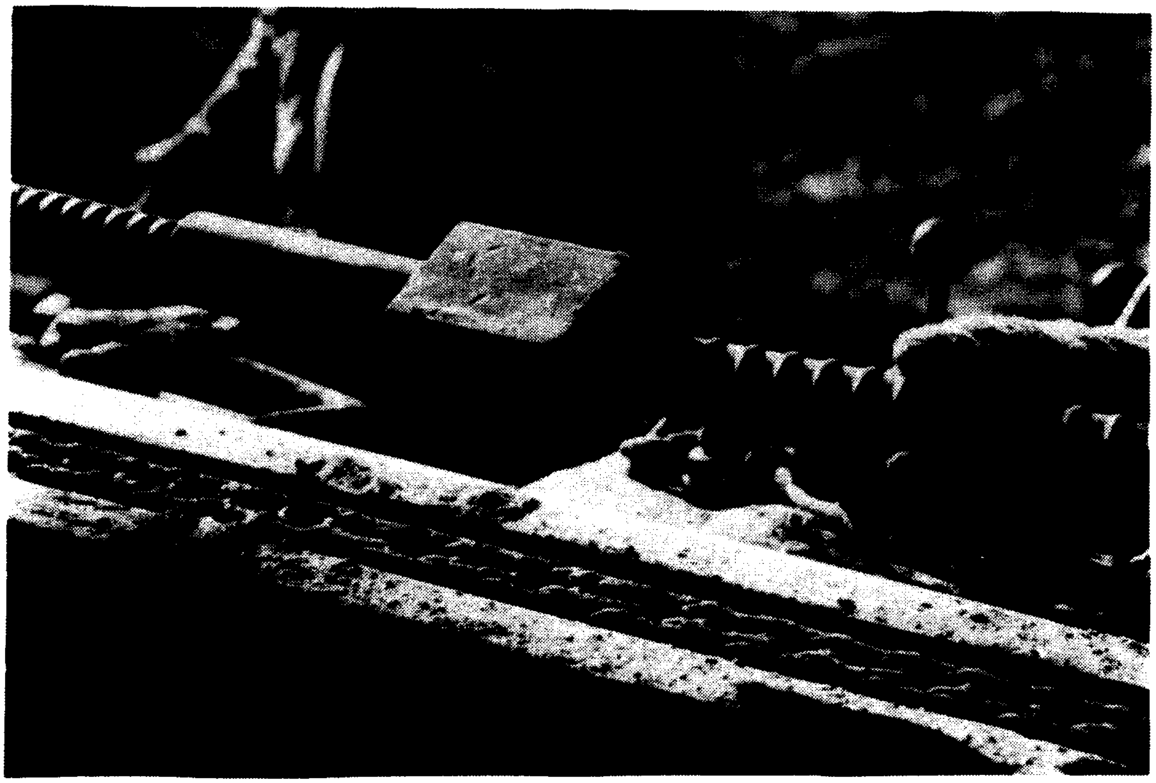

Figure 18. Drive box for rockbolt installation

chiseled to near perpendicularity to the bolt. A pneumatic hammer or "Bush Hog" was used. This procedure was barely adequate, often times causing chunks of rock to come out, breaking off to planes of weakness. This milling procedure was the major time consumer, often requiring 1 or 2 hr per hole to create a usable face.

107. Pull equipment setup. An 8-in. square, 1-3/4 in. thick bearing plate was placed over the rockbolt onto the rock face. Two circular beveled washers were then placed on top of the faceplate. The beveled washers could be rotated to compensate for the face being up to 5 deg off perpendicularity. Due to the poor performance of the "Bush Hog," the rock face was often greater than 5 degrees off perpendicularity. When this happened, rectangular beveled washers were placed between the face plate and rock surface as needed. The circular beveled washers were placed on top of the bearing plate followed by the load cell and another bearing plate. A nut was snugged up onto the rockbolt and then the circular beveled washers were oriented to position the load cell as near perpendicular to the bolt as possible. This arrangement is shown in Figure 19. Note that the rock surface under the face plate is not entirely even.

108. The jack was then placed on the bolt, followed by the nut. A seating load of approximately 12,500 lb (350-psi. jack pressure) was applied as an alignment load. The transducer arms were attached and the transducer oriented parallel to the bolt. The transducer was zeroed at this load. The bolt with load cell, jack, and displacement-measuring transducer are shown in Figure 20.

109. Test procedure. The original test plan intended to utilize an x-y plotter, calibrated in pounds and inches to observe and record load versus strain. The advantage of this instrumentation was that all the data were observed in real time. Unfortunately, the plotter was inoperable when it was unpacked at the site. Attempts to repair or replace the plotter proved to be impractical in the time constraints imposed by the construction schedule.

110. In addition to the system above, an HP3421a data acquisition system was brought to the site for use during creep tests. The data recorder was suitable for use during the pull tests but not at the desired loading rates. The HP recorder samples the data inputs at discreet time intervals rather than providing a continual recording. The disadvantage of this type of recorder was that the test was conducted in a somewhat blind manner. Only a

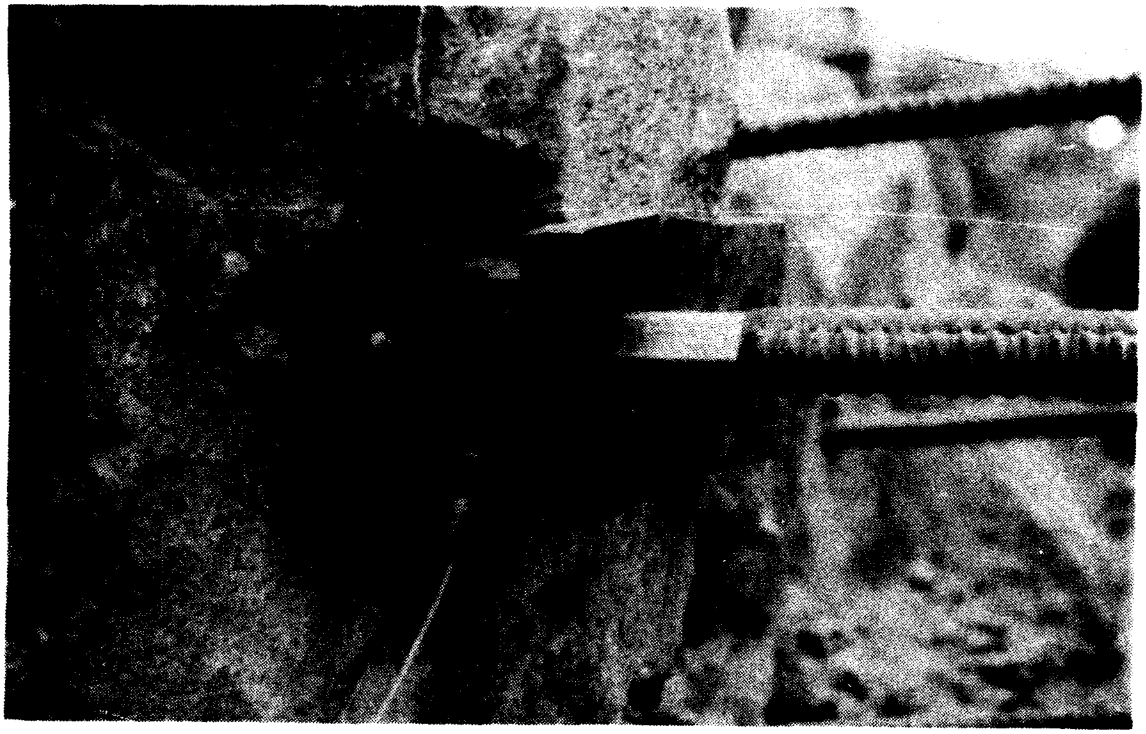

Figure 19. Alignment setup using beveled washer

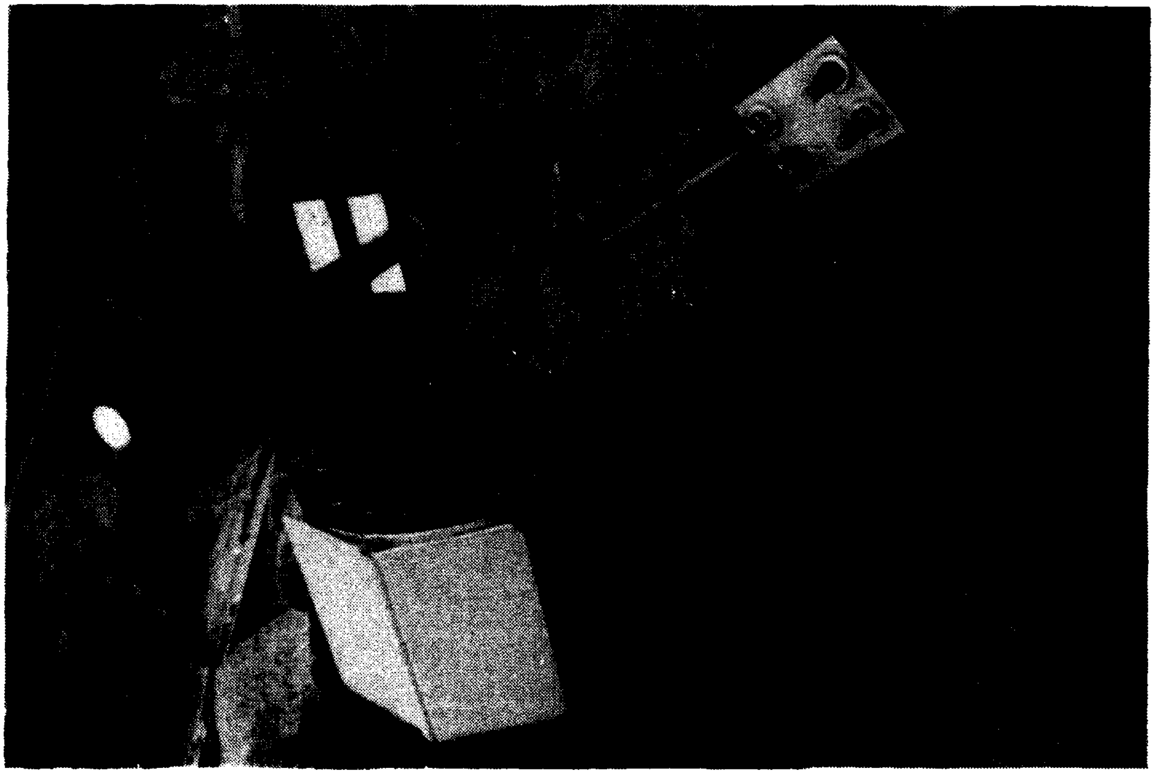

Figure 20. Jack and instrumentation ready for pull test

delayed look at the bolt's performance was obtained while testing was in progress. Since the data recorder took a reading every 5 sec, the load was increased every 10 to 15 sec.

111. The load increment was 350 psi, or about 12,500 lb. The load was applied until anchor failure or until the yield strength of the bolt, roughly 190,000 lb was approached. The bolt was pulled an additional 0.5 in. upon reaching failure. When the resin proved to be stronger than the yield strength of the bolt, the bolt was pulled 0.1 to 0.25 in. more and then unloaded. Frequently, a bolt with no apparent grout failure was unloaded and reloaded with coarser increments to assure the grout integrity.

Test results

112. Test results for the Bonneville series of tests are found in Appendix B. The data include pull test tables listing the variables, maximum load applied, and pull strength per inch (load divided by the grout column in inches).

113. In general, if the maximum load shown on these tables approaches or exceeds 150,000 lb, the grout bulb or column would likely hold to bolt failure. Where the maximum load is substantially less than 150,000 lb, the grout bulb was pulling out of the rock. The guaranteed bolt yield strength was 187,000 lb. Specific results for each series of tests follow.

114. Series 1. Table B1 in Appendix B shows the data obtained for the control bolts. Bolts were installed dry, three bolts each at nominal 2-, 4-, 6-, and 8 ft of grout length.

115. The pull strength of the shortest grout column was substantially less than the longer grout columns. This indicated that 2 ft of grout is insufficient for a No. 11 bolt. Unusually low readings were obtained for tests 3 and 7. These anomalies are believed to be the result of boreholes which were not cleaned.

116. Tests 1-10, 1-11, and 1-12 were conducted on rockbolts that were pushed to the back of the hole and then spun to mix the resin. Bolt 1-10 failed at a load of 165,000 lb exhibiting a strength of 1,718 lb per grouted in. Bolt 1-11 failed at 183,000 lb exhibiting a strength of 1,906 lb per grouted in. Bolt 1-12 failed at 206,000 lb exhibiting a strength of 2,145 lb per grouted in. The average pullout strength of these bolts was 1,923 lb per grouted in., approximately 65 percent of the average strength of the rockbolts that were spun into the hole during insertion. Spinning while inserting is

superior and is the recommended procedure, but even the poorer installation practice provided satisfactory results.

117. Pushing the rockbolts into the hole prior to spinning was the result of the bolt being longer than the boom on the drill. The long grouted length apparently compensated for the lower strength per inch of the grout. The lower performance of these rockbolts prompted the Portland District to require the contractor at Bonneville to spin the bolt for at least the last 10 ft of installation, thus ensuring adequate resin mixing in the anchor zone of the rockbolt.

118. Series 2. Table B2, depicting the submerged installation data, is remarkably similar to the dry test data. The 2-ft grout length was insufficient for the large rockbolt diameter, and one erratic result, Test 2-5, was obtained. The real significance is that there was no difference in performance whether rockbolts were installed dry or submerged.

119. Series 3. Table B3 provides the results of dry pull tests intended to examine the effects of borehole diameter. This test series was run because the borehole diameter used at Bonneville was somewhat larger than the diameter recommended for a No. 11 bolt. The larger diameter was necessary because the long holes planned were deeper than available drill steel. This meant that couplings had to be used to join sections of drill steel. The 2.0-in. maximum diameter did not provide clearance for the coupling. While the data showed an apparent proportionality between bore diameter and pull strength, the data are not statistically significant. The important finding was that the oversize borehole did not create a loss of pull strength.

120. The overriding effect discovered during this series was the borehole cleanliness effect. This unplanned, variable amount of residual mud cake on the inside of the hole interfered with normal grout-to-hole interlock. It is the probable cause of the wide data scatter.

121. Series 4. Table B4 provides the results of wet pull tests intended to examine the effect of borehole diameter in wet installation. The correlation between bore diameter and pull strength, as in Series 3, existed with grout column lengths of 3 ft or less. The correlation disappeared with grout lengths at 4 ft or greater.

122. One bolt, Unit 4-11, was not tested as the bolt was too short and did not stick out far enough to grip.

123. On the average, the wet installed rockbolts provided slightly

higher strength per inch results than the dry units. This is attributed to the fact that the wet holes were subjected to some water flushing as they were filled with water using the drill. This likely removed some mudcake and provided slightly better contact of the grout bulb and the rock.

124. Series B and L. The results of these tests are shown in Table B5. These test holes were thoroughly flushed with water before installation. They demonstrated a significant pull strength increase over air cleaned holes. The 2-1/2-in. diam holes had an average strength per inch of 3,293 lb. The 2-1/8-in. holes had an average strength per inch of 4,334.

125. Recommendations by resin manufacturers, as well as the US Bureau of Mines, suggested that the borehole diameter should not exceed the bolt diameter by more than 1/4 in. These tests were all conducted on bolts installed in holes greater than 1/2 in. larger than that recommended by the Bureau's tests. Two possible explanations are offered accounting for the acceptable performance of the larger boreholes used in these tests. First, the bolt used in these tests is oblong shaped in cross section, whereas the bolts used in the Bureau's tests were round. The oblong shape of these bolts provides an excellent configuration for mixing the resin. The second explanation is bolt wobble. The bolts used in these tests were much longer than the bolts used on the Bureau's tests. The long bolts would have a tendency to wobble in the hole during installation. This would have a positive effect on resin mixing. A shorter bolt may spin more concentrically in the borehole, reducing the blending effect.

126. Series T. Series T were tests involving "dynamic" water flow out of the borehole. Table B6 shows the results. This test series showed excellent pull strength in both 2-1/8- and 2-1/4-in. boreholes. There were, however, two failures in the 2-1/8-in. boreholes, not related to borehole size. Anchor T-2 pulled at 43,902 lb. The grout length could not be measured and therefore was probably very short. The grout likely extruded into rock fractures.

127. Similarly, Unit T-4 pulled out at the seating load, about 12,000 lb. Again, the probable cause was grout loss into the rock fractures.

128. Series S. This series employed 18-ft rockbolts and a nominal grout length of 10 ft. These bolts simulate the configuration used for production anchoring at the new Bonneville Lock. Pull strength of the grout could not be tested as the bars reached yield strength first. Short-term

creep tests were conducted on bolts S-1, S-2, and S-3 following the pull tests. The recorded movement after 3 to 12 hr was less than 0.001 in.

129. Another experiment run on this series was to determine if placing a cyclic load on the rockbolts would aid in the detection of anchoring flaws more quickly than the straight graduated pull. Loads were cycled from 50 to 150 kips. This procedure appeared to have no advantages.

Summary of results

130. These tests demonstrated the suitability of polyester resin as an anchor grout material at the New Bonneville Navigation Lock. The key issue driving this investigation was to determine the performance of a rockbolt when water is present during installation.

131. This investigation determined that water present during installation has a negligible effect on the performance of the rockbolt. Figure 21 shows the overall results of the Bonneville pull tests. In summary, rockbolt pull strength rises proportionally with grout length until the yield strength of the bolt is reached. For the No. 11 Dywidag bolt, yield occurs at a grout length of about 55 in. In fact, submerged installation actually increased the strength of a series of test bolts when compared with the equivalent dry test matrix (Tables B3 and B4). The wet installed rockbolt pull-out strength increase led to an investigation into the effects of hole cleanliness. Those tests showed a significant strength increase when the borehole is properly washed out with water.

132. The investigations into borehole diameter effects concluded that borehole sizes up to 2-1/4 in. are acceptable for the use of a No. 11 (1-1/8 in.) Dywidag rockbolts.

133. Finally, the short creep tests conducted at 100,000 lb detected movement less than 0.001 in. Creep failure of the anchors at Bonneville at the pretension load of 57,000 lb is quite improbable.

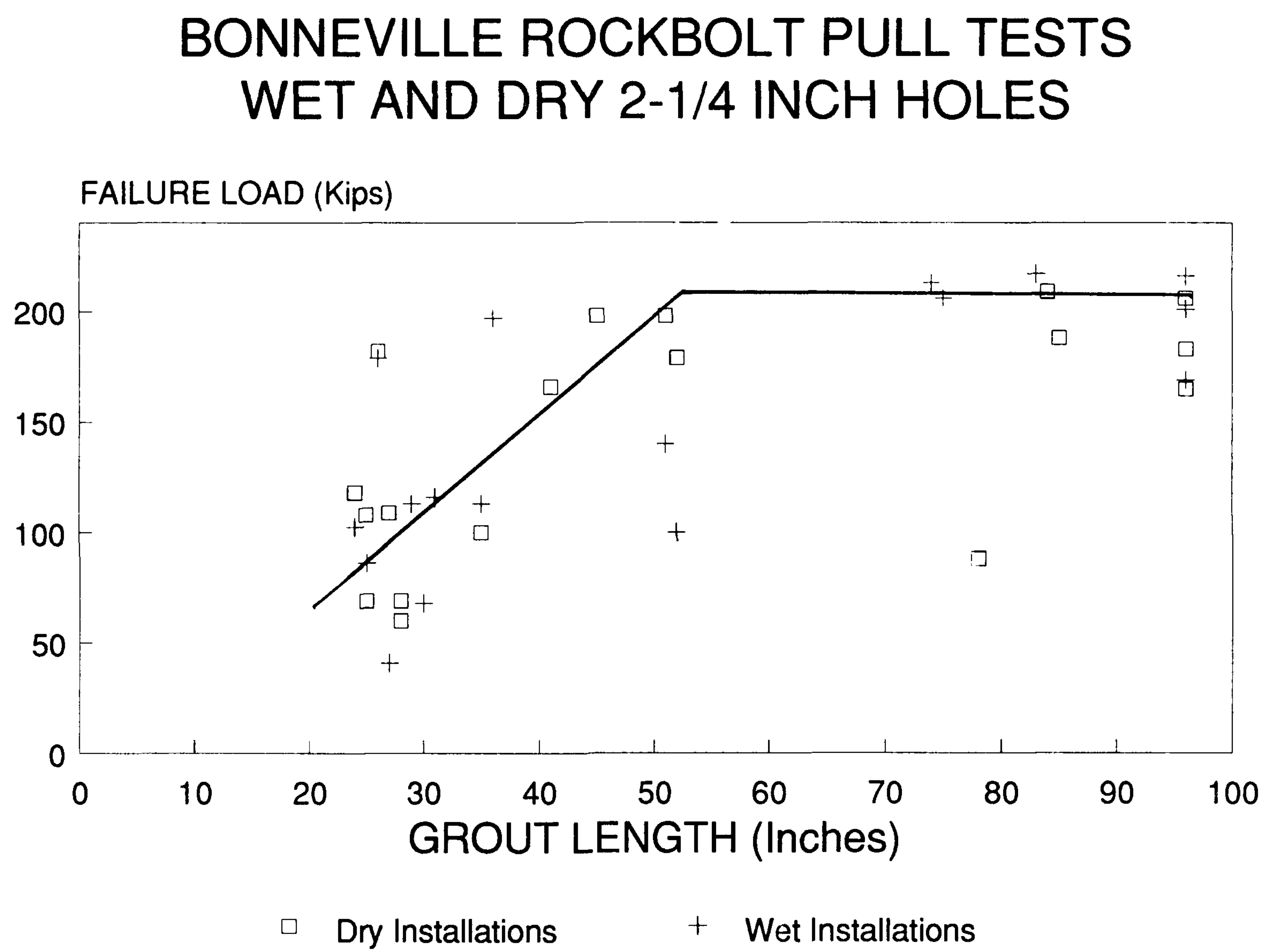

Figure 21. Bonneville pull test results

PART III: DISCUSSION OF JOINT EFFECTS

134. When rockbolting or installing anchors in fractured rock, two additional factors must be considered when utilizing polyester resin grout.

a. Undergrouting. This problem occurs if the resin, under the pressure caused by installing the bolt, moves out into the formation cracks rather than filling the annulus between bolt and rock bore. This phenomenon may occur under either wet or dry conditions.

b. Dynamic water. Water flowing out of a borehole is always an indication of jointed ground, with the added characteristic that at least one intersected joint contains water. A less obvious form of dynamic water would be the case where water flows through but not necessarily out of the borehole. Dynamic water can interfere with resin polymerization by both dilution and cooling.

The Krysa report (1982) first identified the problem of dynamic water interference with proper polyester grout polymerization. The report described the grout bulbs of rockbolts pulled from the Monongahela Lock 3. Major portions of grout column were destroyed or missing from the pulled bars.

Laboratory Test Setup

135. A brief test series was conducted at WES in July and August 1987 to provide a cursory evaluation of bolts installed under dynamic water conditions. The main purpose of the test was to determine the undergrouting potential of a single flowing fracture when a bolt was installed with polyester resin. The degree of undergrouting was gaged by measuring the grout column and by conducting pull tests.

136. The tests were conducted using a 4-ft cube of concrete with a 3-in. hole drilled through the middle. The cube was then split in half such that the hole traversed the fracture. The block was bolted back together. Test holes were drilled from the face parallel to the fracture, so that the holes intersected the fracture. Water was injected into the fracture by pressurizing the 3-in. hole. The perimeter of the block was sealed, forcing the water out of the borehole.

137. Tests consisted of installing a 3-ft long No. 6 Dywidag bolt into a 24 in. deep, 1-in. diam borehole. Celtite fast-set was used for the anchor grout. Pull tests were conducted and both load and displacement were

measured.

Dry control tests

138. Five dry holes were used to provide a baseline for comparison with the wet tests. As shown in Table 3, all dry installations created an anchor capable of exceeding the yield strength of the bolt.

Table 3

Dynamic Water Installation Test

Face	Test	No. Resin Cartridges	Flow Rate	Pull Test Result
1	1	1	1.9 gpm	y
1	2	1	1.8 gpm	20,000
1	3	1	2.0 gpm	27,500
1	4	1	1.6 gpm	y
1	5	1	2.6 gpm	y
2	1	2	dry	y
2	2	2	dry	y
2	3	2	dry	y
2	4	2	dry	y
2	5	2	1.0 gpm	y
2	6	2	dry	y
2	7	2	0.7 gpm	y
2	8	2	1.8 gpm	y
2	9	2	1.1 gpm	y
2	10	2	1 gpm	y
2	11	2	4.0 gpm	y
2	12	2	4.0 gpm	y
2	13	2	5.3 gpm	17,250
2	14	2	1.3 gpm	y

Note: y = bar yield, 32,000-lb load

Wet test, one cartridge

139. One cartridge of resin per bolt was used to anchor five test bolts in the block. The bolts were installed under flow rates varying from 1.8 to 2.6 gpm. Two of the bolts failed to hold loads up to the yield strength of the bar. The Test 2 bolt failed at approximately 20,000 lb, while the Test 3 bolt failed at approximately 27,500 lb. The remaining three bolts held loads in excess of the yield strength of the bar.

Wet test, two cartridges

140. Two cartridges of resin per bolt were used to anchor nine test

bolts in the block. The bolts were installed under flow rates varying between 0.7 gpm and 5.3 gpm. Only one bolt failed to hold a load up to the yield strength of the bar. The borehole for this bolt was installed under a flow rate at 5.3 gpm. The aperture of the fracture was measured to be 0.20 in. prior to bolt installation. The grout length of the failed bolt was only 12 in. long, roughly 30 percent of the anticipated grout length for two cartridges of resin.

Summary

141. These brief tests showed that bolt performance may not always be judged by flow rate when bolting under dynamic water conditions. Pull tests showed that three of the nine bolts installed under dynamic conditions failed to hold the yield strength of the bar. One of the failures occurred at the highest flow rate while the other two failures occurred at moderate flow rates. The remaining six bolts held loads in excess of the yield strength of the bar.

142. These tests were not extensive enough to develop a predictive method of determining when undergrouting of the bolt was most likely to occur. It does, however, serve as a warning that a flowing borehole is a sign of potential problems. The solution may consist of one or more of the following steps.

- a. Conduct performance tests on all bolts installed under such conditions.

- b. Pregrout the holes using a cement grout material. The hole can be redrilled while the cement is still green.

- c. If the bolt pulls out on the test, a clean bar could be reinstalled into the same hole. The original resin has probably functioned as a pregrout and will reduce resin loss on the second installation attempt. The hole should be cleaned out by running the drill into it after the resin has fully cured.

PART IV: BONNEVILLE PRODUCTION QUALITY CONTROL

Background

143. The Bonneville, Bureau of Mines, and WES tests had established that the integrity of polyester grouted rockbolts, within limits, was sound. Properly installed bolts, even installed submerged, or under dynamic water conditions, with grout lengths of 3- to 4-ft minimum, will secure a bolt to its yield strength. The Bonneville Navigation Lock project would use 20- to 60-ft long bolts with grout lengths of 10-ft minimum. Nevertheless, the US Army Engineer District, Portland, wanted to maintain the highest degree of control possible in order to assure structural integrity of the construction.

144. Each bolt was required to have a proof test. Results and details of its installation were recorded on a data sheet for every bolt. A typical data sheet is shown in Figure 22.

145. Included were location, length of the bolt, hole depth, water presence, rock condition, and spin rpm and time.

146. Quick-set polyester resin grout was used in sufficient amounts to obtain a 10-ft anchor length. The remainder of the hole was filled with slow-set resin. Proof tests were conducted and the bolt was "locked off" (nut tightened) with a residual tension of 57,000 lb, all before the slow-set time polyester hardened.

Proof test methods

147. The proof test adopted was similar but more severe than the recommendations of the Post Tensioning Institute (PTI) (1986). Each bolt was tested in the time interval between the quick-set anchor resin setting and the slow resin setting. The bolt being tested was pulled to 80 percent of its guaranteed ultimate strength while recording elongation. For a grade 150, No. 11 bolt, this load is 187,000 lb. Then a 5-min creep test was conducted by holding the load and continuing to measure any elongation for 5 min. After the creep test, load was lowered and the bolt locked off.

148. Normally, the PTI test consists of a proof test 1.33 times the lock off or design load. In this case, both lock off and design load were 57,000 lb. Thus, the PTI recommended pull was 75,810 lb. The test load, nearly 3.3 times the design load, was considered ultraconservative in order to absolutely confirm bolt integrity.

BONNEVILLE LOCK EXCAVATION 2197
ROCK BOLT INSTALLATION ASBUILT DATA

INSTALL DATE: 5/25/88 MARK #: 2197 TYPE : SHS
FACE : N TEMP : 60

STA (FT): 2434.20 ELEV (FT): 15.75 -LT/+RT: 48.50
LFFSET(IN): 3.0 VFFSET(IN): 1.0

BEARING : 90

LENGTHS: DRILL (FT): 36.40 BOLT (FT): 40
ANCHOR(FT): 10 PROJECTION(FT): 3.6

DIAMETER OF HOLE(IN): 2.125

WATER: NONE DEPTH: FLOW :

CAVING: NONE DIAM : DEPTH:

CASING: REQD : No DIAM : DEPTH:

GROUT : REQD : No VOL : DEPTH:
TIME INT :

R.P.M. for 10 FT ZONE: 122

MIXING TIME FOR 10FT ZONE: 30

DEPTH TO RESIN AFTER BOLT INSTALLATION: 0

ULTIMATE TENSION : 187500 GUAGE NO. :LB6SHS RAM NO. :110304

STRESSING

LOAD	**GUAGE(psi)**	**ELONGATION(in)**
Alignment	500	0.000
0.25P	1050	0.068
0.50P	2100	0.431
0.75P	3200	0.754
1.00P	4200	1.048
1.25P	5300	1.362

CREEP TEST	0 SEC	1.362
	30 SEC	1.366
	2 MIN	1.366
	5 MIN	1.368

PASS : **Yes** MAX TENSION IF FAILED:
LOCK OF TENSION: 57500.0

COMMENTS:

Figure 22. Typical anchor quality control log

149. PTI recommends that the first three installations and then a percentage of the remaining bolts be tested. This percentage is selected by the engineer in charge but would seldom exceed 5 percent. In this case, however, because the anchor was used as a critical part of the lock structure, every bolt was tested.

Acceptance and failure criteria

150. According to the PTI standards, an anchor shall be acceptable if:

a. The total elastic deformation obtained from a performance test exceeds 80 percent of the theoretical elastic elongation of the stressing length, and is less than the theoretical elastic elongation of the stressing length plus 50 percent of the bond length.

b. The total movement obtained from a proof test measured between 50 percent of the design load and the test load exceeds 80 percent of the theoretical elastic elongation of the free stressing length for the respective load range.

c. The creep rate does not exceed 0.080 in. (2.0 mm) per logarithhmic cycle of time during the final log cycle of the performance test, proof test, and/or creep test regardless of tendon length and load.

d. The initial lift-off reading shows an anchor load within 5 percent of the specified lock off load.

e. The lift-off test shows an anchor load within 10 percent of the specified transfer load.

The following definitions apply to resin grouting.

a. Stressing length. The length of the bolt between the resin bulb (the fast-set resin anchor) and the bearing plate. The portion of the bolt which is free to elongate. In the Bonneville installations this length was grouted with slow-set resin.

b. Bond length. The length of the anchor grout bulb. In the case of resin bolts "bond" is in reality a friction or mechanical grip of the resin and asperities in the borehole.

c. Tendon length. The complete anchor length, stressing length plus bond length.

d. Lift off. When pulling on a bolt having already been stressed and locked off, the point at which the plate moves off of its seat.

151. The hole depth and the bolt elongation obtained from the proof tests were compiled on a LOTUS spreadsheet. The program calculated the theoretical elongation for a bolt installed in the depth hole reported. The theoretical elongation was then compared with the measured elongation, and the bolt categorized as to how it compared. The results of the computer programs, plotted along with the average measured results, are shown in Table 4. There are 5 categories of bolt elongation, as shown in Figure 23. The definitions of the categories are listed below:

Type 0. This category does not refer specifically to bolt performance, but indicates that the face collapses or the bolt could not be stressed due to improper physical conditions.

Type 1. The elongation is in the first 80 percent of the free length of the bolt; unacceptable.

Type 2. The elongation is between the first 80 percent of the free length and the front of the anchor zone; acceptable.

Type 3. The elongation is between the front and 50 percent of the anchor zone; acceptable.

Type 4. The elongation is between 50 percent and the end of the anchor zone; acceptable.

Type 5. The elongation is outside of the anchor zone, which implies the anchor is not holding the bolt due to failure of the bolt-to-resin or resin-to-rock interface.

According to the PTI, Types 2 and 3 indicate acceptable bolt performance. Type 4 was added to the acceptable categories for Bonneville because the test load was much greater than the lock off load.

<u>Results</u>

152. The pull test results, listed by length of bolt and type or category of result, are shown in Table 4.

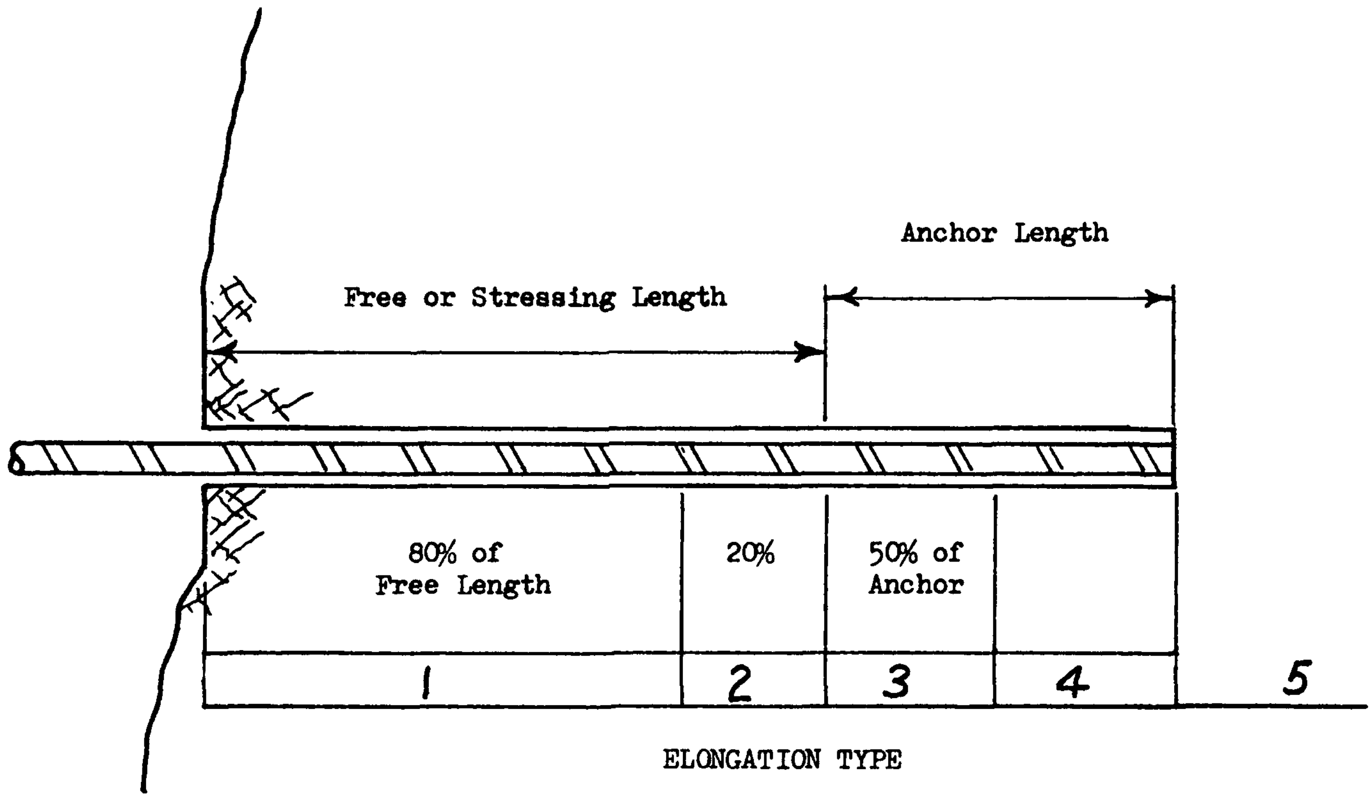

Figure 23. Bolt elongation and anchor zones

Table 4

Bonneville Rockbolt Production Bolting

Bolt Lengths ft	Elongation Type Number of bolts in category/percentage of population						
	0	1	2	3	4	5	Total
20	108/8	73/5	145/10	708/49	298/21	102/7	1434
30	45/6	41/6	138/20	342/49	90/13	37/5	693
40	15/3	62/14	115/26	191/43	59/13	6/1	448
50	43/10	204/49	166/40	5/1	0/0	0/0	418
60	5/5	54/50	41/40	5/5	0/0	0/0	105
Total	216/7	434/14	605/20	1,251/40	447/14	145/5	3,098

A total of 3,098 bolts tests were observed and data tabulated. Results in each category were:

a. Type 2, 3, or 4 -- satisfactory, 75.3 percent.

b. Type 0 -- invalid test, 7.0 percent.

c. Type 1 -- low free length, 14.0 percent.

d. Type 5 -- pulling out, 4.7 percent.

153. The results of the production bolt proof testing show that 4.7 percent of the bolts exceeded the maximum allowed elongation. Under normal posttensioning practice, either the contractor would have been required to install an additional anchor or the anchor would have been locked off at a lower load. Since the lock-off load was so much lower than the test load, there was no need to replace the bolt or lock it off at a lower load. The tests were conducted primarily to maintain the level of quality and provide a means of assessing any deviations in ground or installation conditions. The prime objective was to prevent a cluster of bolt failures, which was accomplished.

154. The results of the computer program which calculated allowable elongation for each length of bolt are shown in Figure 24. In addition, the average elongation for each bolt type is plotted. Figures 25 through 29 are bar charts showing the types of elongation obtained for 20-, 30-, 40-, 50-, and 60-ft long anchor bolts, respectively.

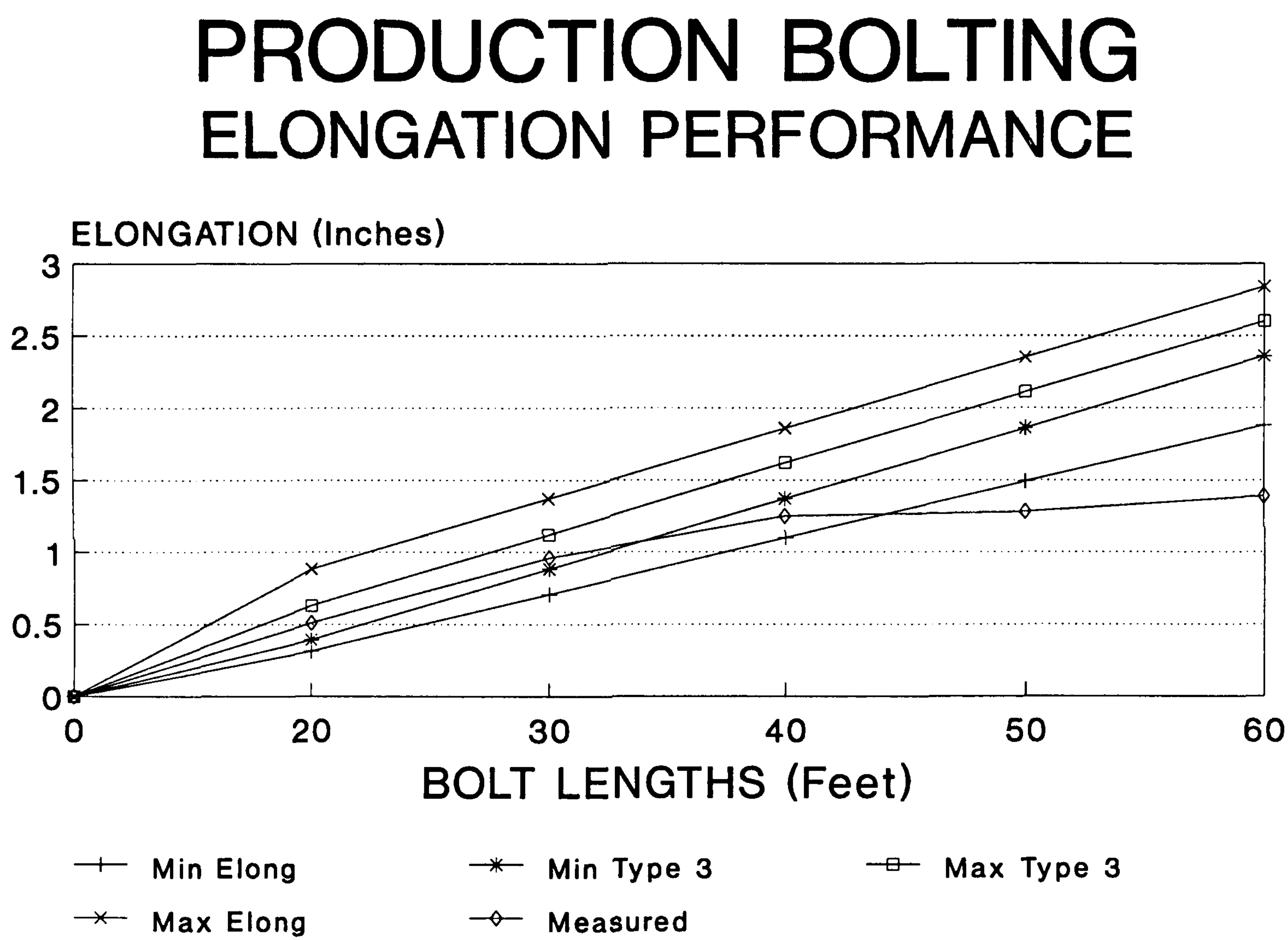

Figure 24. Bonneville Navigation Lock performance of production bolting

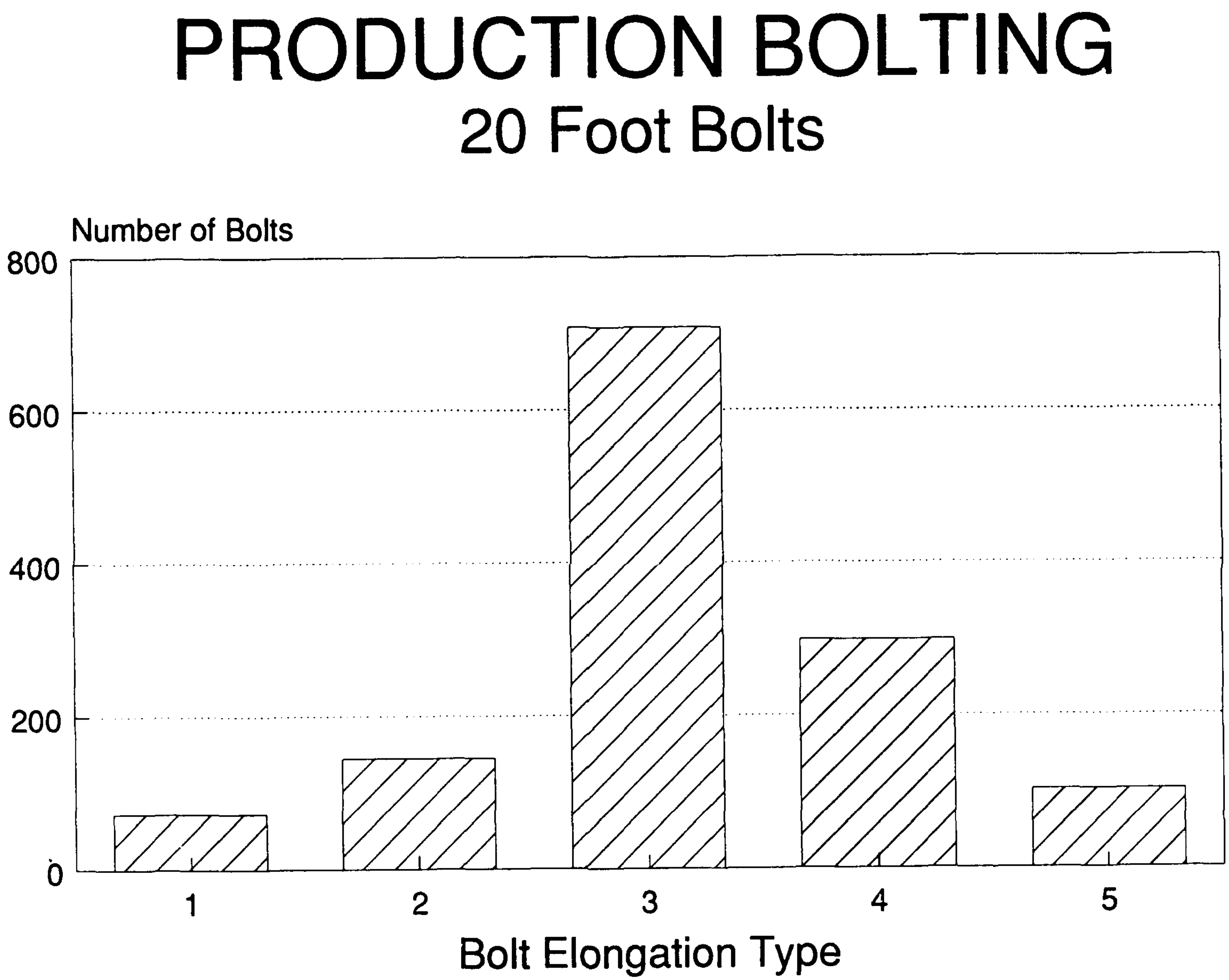

Figure 25. 20-ft bolts, elongation type

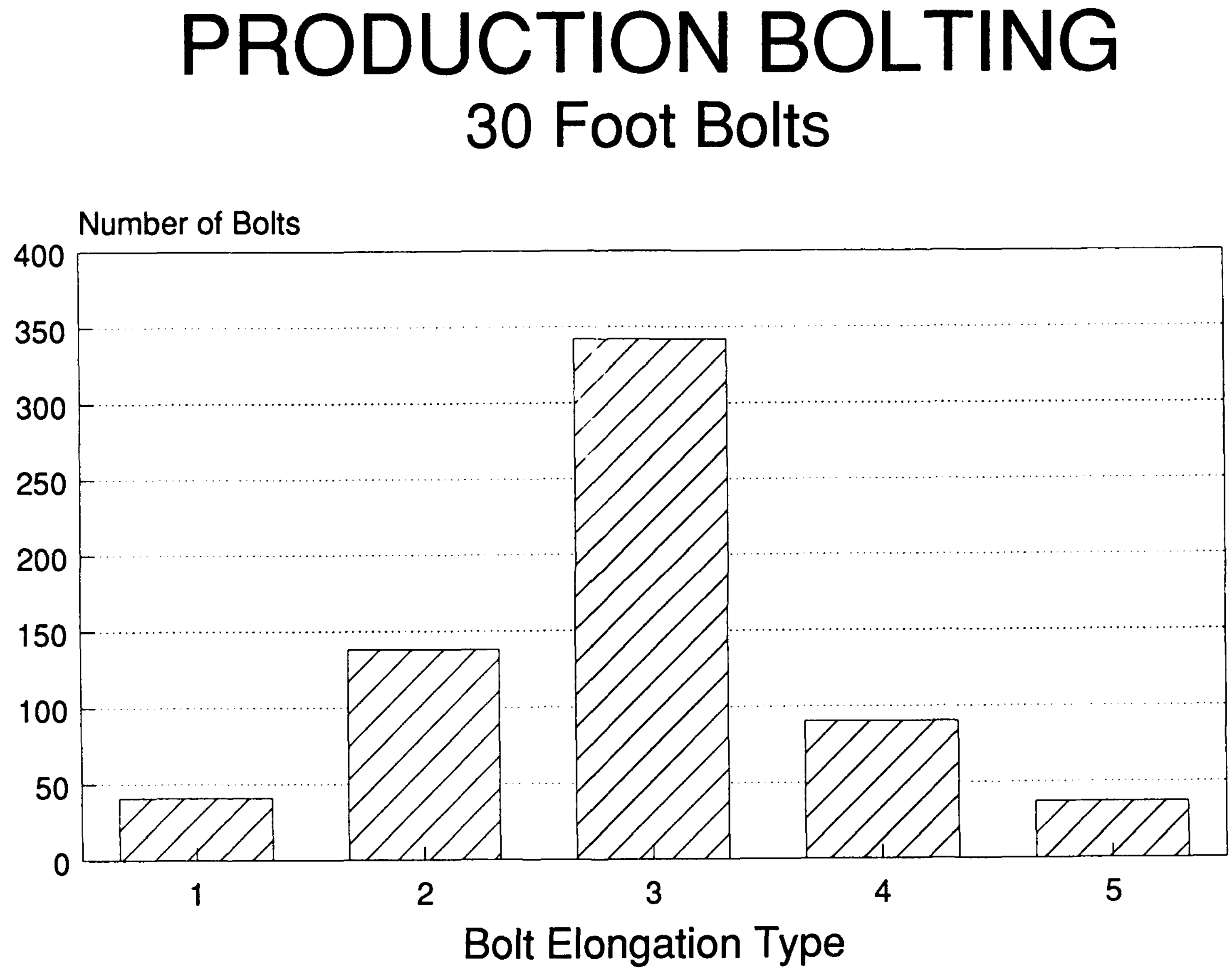

Figure 26. 30-ft bolts, elongation type

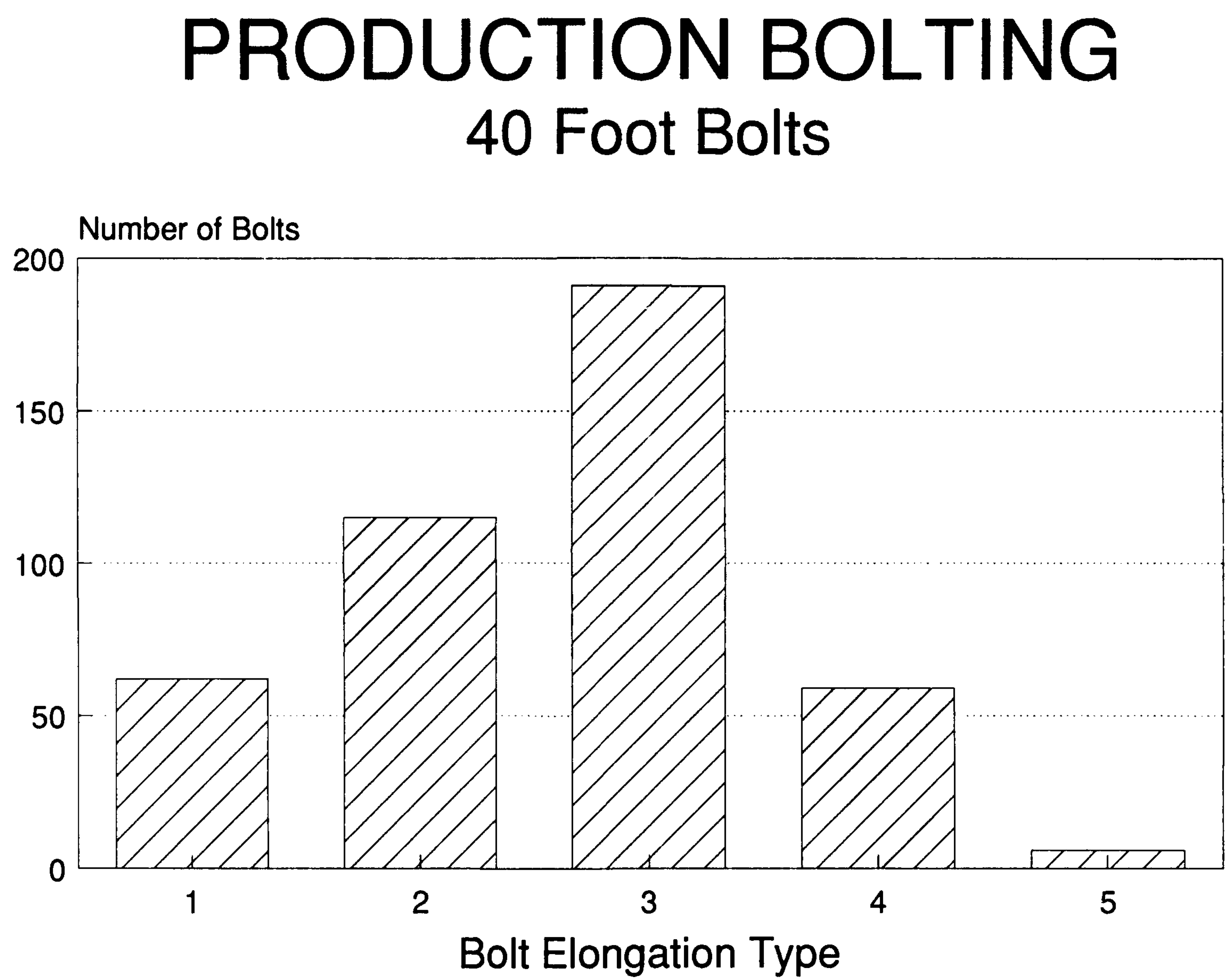

Figure 27. 40-ft bolts, elongation type

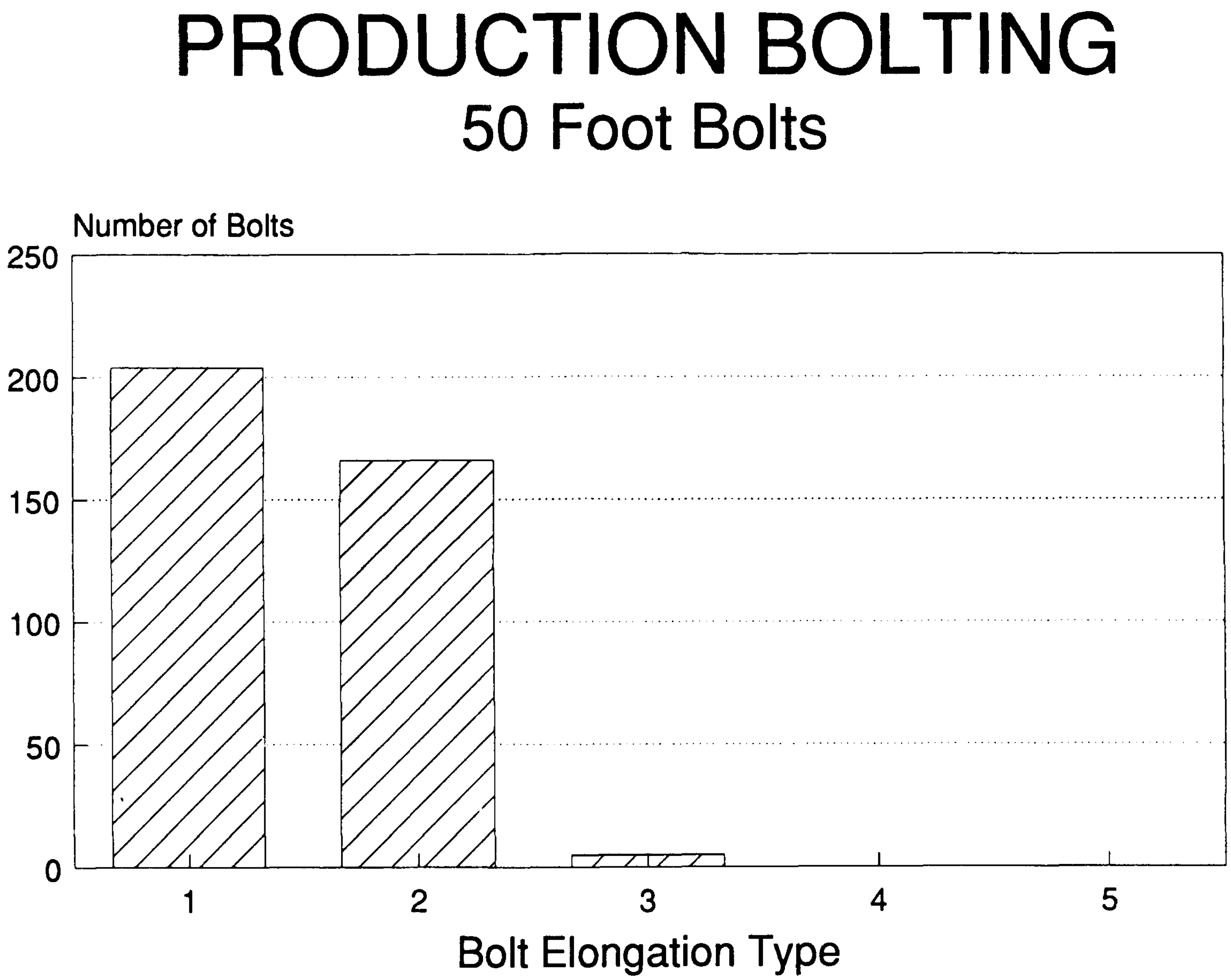

Figure 28. 50-ft bolts, elongation type

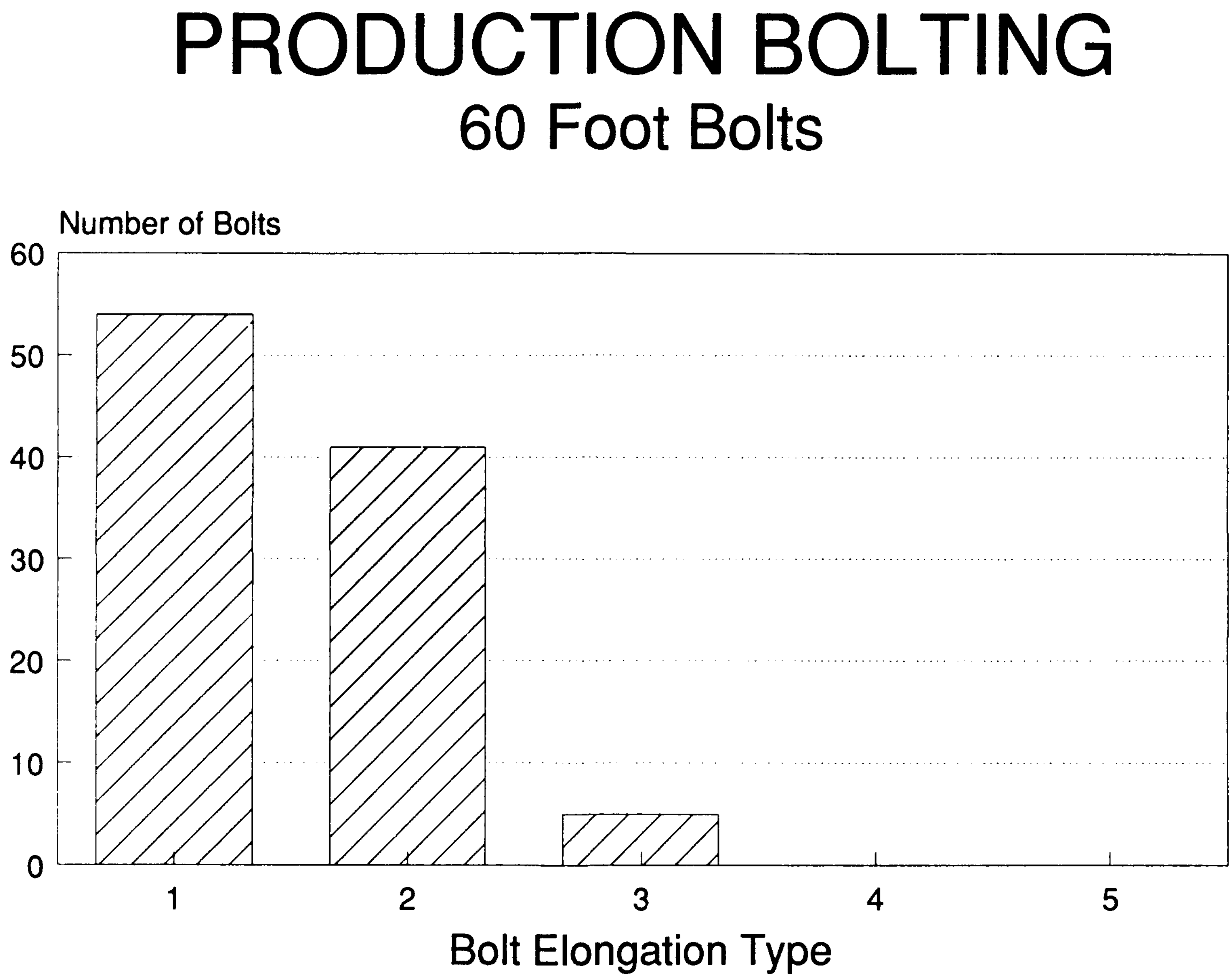

Figure 29. 60-ft bolts, elongation type

155. The 20-ft bolts produced bell-shaped distribution with a bias toward the elongation types of 4 and 5. The 30-ft bolts also produced a bell-shaped curve, but biased toward the lower elongation categories of 1 and 2. The proportion of the 20- and 30-ft bolts in Type 3 was nearly identical, and by far most frequent. The trend toward a greater percentage of bolts in the lower elongation categories continued with the 40-ft bolts, as shown in Figure 27, where 40 percent of the bolts are in categories 1 and 2. The 50-ft bolts continue with 89 percent of the bolts in categories 1 and 2, as shown in Figure 28. Finally, 90 percent of the 60-ft bolts are in categories 1 and 2, as shown in Figure 29.

156. The decreasing elongation with increasing bolt length indicates that the bolts are not elongating sufficiently. The three bands in Figure 24 show the upper and lower elongations necessary for categories 2, 3, and 4 for bolt lengths of 0 to 60 ft. Plotted within the bands is the actual average elongation of the bolts installed at Bonneville. With category 2 being the lowest minimum elongation allowable, bolts greater than approximately 46 ft long will fail to reach the minimum acceptable elongation. A bolt 37 ft long will elongate only enough to reach the anchor zone.

157. The low elongations imply that the bolt is not being tensioned to the desired depth in the rock, resulting in loss of active force being transmitted into the rock. The unstressed portion of the bolt, or "shadow zone," will, however, act as a rock dowel or passive anchor.

158. The suspected cause of the low elongations was hole crookedness. A crooked hole will cause the bolt to rub against the sides of the borehole wall, absorbing the tension of the bolt in friction. The other possible explanation was that the slow-set resin in the free length zone was setting prematurely. This also would prevent the bolt from elongating to the anchor zone. Further investigation showed that the contractor's procedure and the resin performance were acceptable, and that premature resin set was not the cause for the low elongations. Consultation with a Bureau of Mines expert on resin systems verified that hole crookedness was the probable cause of the low elongations.

159. The consequences of the loss of prestress in the end of these long bolts are difficult to assess. Rock instability may result in some anchoring applications where a given prestress is required at a given depth in the rock.

However, the shadow zone portion of the bolt still acts as a passive anchor. Perhaps the greatest problem lies in the inability to determine whether the end portion of the anchor is adequately grouted into the borehole. The elongation of the bolt provides this determination.

160. The last possible problem is increased corrosion potential of the bolt. The bolt will be pulled up against the curved sections of the borehole wall, possibly exposing it to corrosive water.

161. One solution to this problem is to telescope the diameter of the borehole. The free length of the anchor would be drilled a larger diameter, perhaps 2-1/2 to 4 in. The anchor zone would be drilled to the diameter required for proper resin mixing for the bolt size used. The anchor zone would be grouted with resin and the free length would be grouted later with cement.

Long-term monitoring

162. Ten load cells were installed in the lock chamber to monitor long-term performance of the anchors. The load cells were placed at five elevations in pairs at two stations, 2392 and 2395. The load cell pairs were located at elevations* of el 44.75, el 30.75, el 16.75, el 2.90, and el -11.25. The load cells along sta 2395 were installed on bolts that were point anchored only with 10 ft of fast-set resin. The rock bolts at sta 2392 were fully grouted. All bolts were tensioned to 57 kips.

163. The bolts at sta 2395 were point anchored to provide a comparison against the fully grouted anchors at sta 2382. The primary objective of the load cell installations was to monitor the rockbolts for load decay. This objective was very difficult to achieve with fully grouted anchors because any load loss in the anchor zone is absorbed in the grouted free length of the bolt. The load cells on the point-anchored bolts would instantly detect load changes between the face plate and anchor zone. The load cell on the fully grouted bolts would detect load changes only after they had been redistributed along the free length to the face plate. Also, should the face collapse on the fully grouted bolt, the tension in that part of the bolt would drop to zero, dropping the load cell reading to zero as well.

164. A plot showing the load versus time for the ten load cells is

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* In this report, elevations are in feet, National Geodetic Vertical Datum (NGVD).

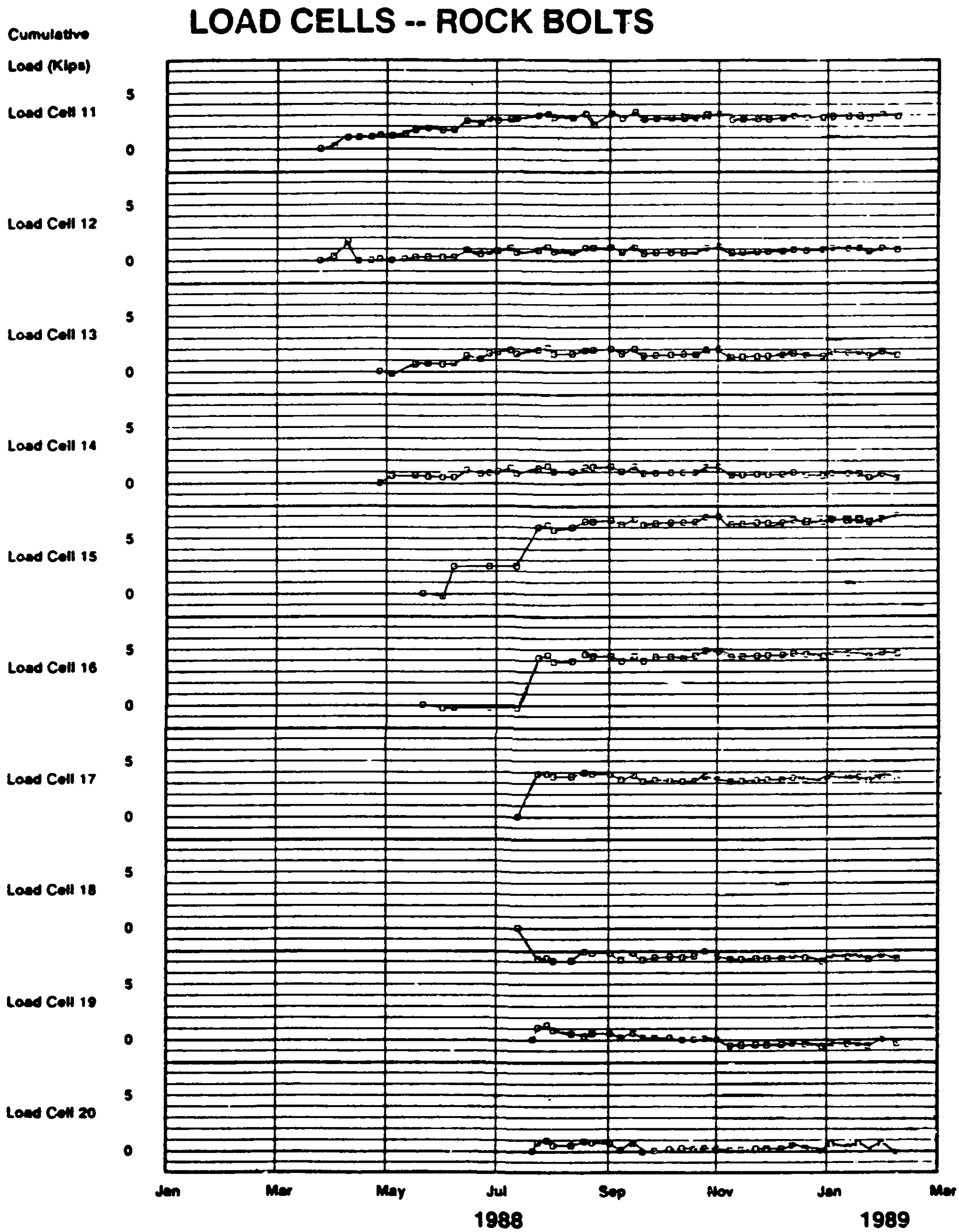

Figure 30. Long-term creep tests, bolts 11-15, point anchored; bolts 16-20, fully grouted

shown in Figure 30. The readings from installation dates to approximately September 1988 are quite erratic due to construction activities in the lock. The record from September onward shows a relative quiescence in the load history of the rockbolts.

Summary

165. The principal finding of these tests showed that, on average, bolts longer than 36 ft will not elongate to the anchor zone. This conclusion is limited to the particular installation conditions employed and the rock type in which the holes were drilled. This data should be used, however, as a guideline for modifying the borehole drilling procedure for prestressed bolts. Precautions should be taken to minimize the chance of a bolt lying against the sidewall of the hole and producing load distribution to an unintended zone of rock through friction or wedging.

PART V: CONCLUSIONS AND RECOMMENDATIONS

166. The following conclusions and recommendations are drawn from the tests described herein, literature research, and vendor data. The list is presented in no particular order.

a. In Series 1, Bonneville tests, three bars were pushed in and then spun. All others were spun while inserting the bolt. Average strength per inch for bolts spun only after insertion was 1,923 lb. Average for the bolts spun while inserting was 3,293 lb per inch. Therefore, bolts should be spun while inserting.

b. Tests by TVA, WES, and the Bureau of Mines all confirmed that rockbolts, dowels, or anchors installed in submerged boreholes less than 2 ft long should not use polyester resin.

c. There is no apparent performance advantage comparing water and oil-based polyester resins.

d. A powder pole should be used to move the cartridges snugly to the bottom of the hole. Using the bolt may rupture the cartridge and cause premature setting of part of the resin.

e. A clean hole is perhaps the most important attribute of proper bolt or anchor installation. Dependable anchoring can not be achieved in a hole with residual debris or mud cake coating the hole.

f. In either dry or wet holes at Bonney Rock, a critical grout length of at least 55 in. is recommended to achieve an anchor which will approach the bolt yield strength. This critical length will vary for different rock types and should be determined experimentally.

g. Submerged water installation does not affect grout except for about the outer 12 to 14 in. Therefore, single cartridge installations should be avoided.

h. To achieve proper elongation in bolts in excess of 40 ft long, the free length should be bored to a larger diameter. This avoids friction or wedging of the bolt against the borehole and subsequent loss of tensioning length.

i. Temperature of installation must be controlled to a reasonable (about 45° F to 90° F) range above or below room temperature.

j. Dynamic water and badly fractured ground present the most severe case for the use of polyester resin. Precautions must be taken to assure that the anchor grout fills the annulus as required and does not instead extrude into voids or cracks.

k. Under the most severe conditions, pull testing each bolt is justified as in the case above. A bolt may have to be installed twice, the first attempt having pregrouted the hole. An alternate is to pregrout holes with cement to close the cracks and voids.

l. Installing proper rockbolts is an iterative process. Accurate logging of variables, close communication between a drilling crew and a stressing crew,and continuous adjustment will achieve the best results.

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APPENDIX A

TO

Report F 7891

Rockbolt Pull Test Data

from

Bureau of Mines,
Denver Research Center Tests

The tables and plots in this Appendix are taken directly from the unpublished Bureau of Mines Report "Effects of Water Filled Holes on Polyester Resin Grout Strength" written by T. E. Cherrier and W. W. Lutzens.

Four groups of data are provided in the following order:

1. A series of twelve computer generated plots of load vs. displacement, the results of the rockbolt pull tests.

2. The twelve raw data sheets from which the plots were derived.

3. Two tables containing hole measurement data.

4. Two tables containing observations made during bolt installation.

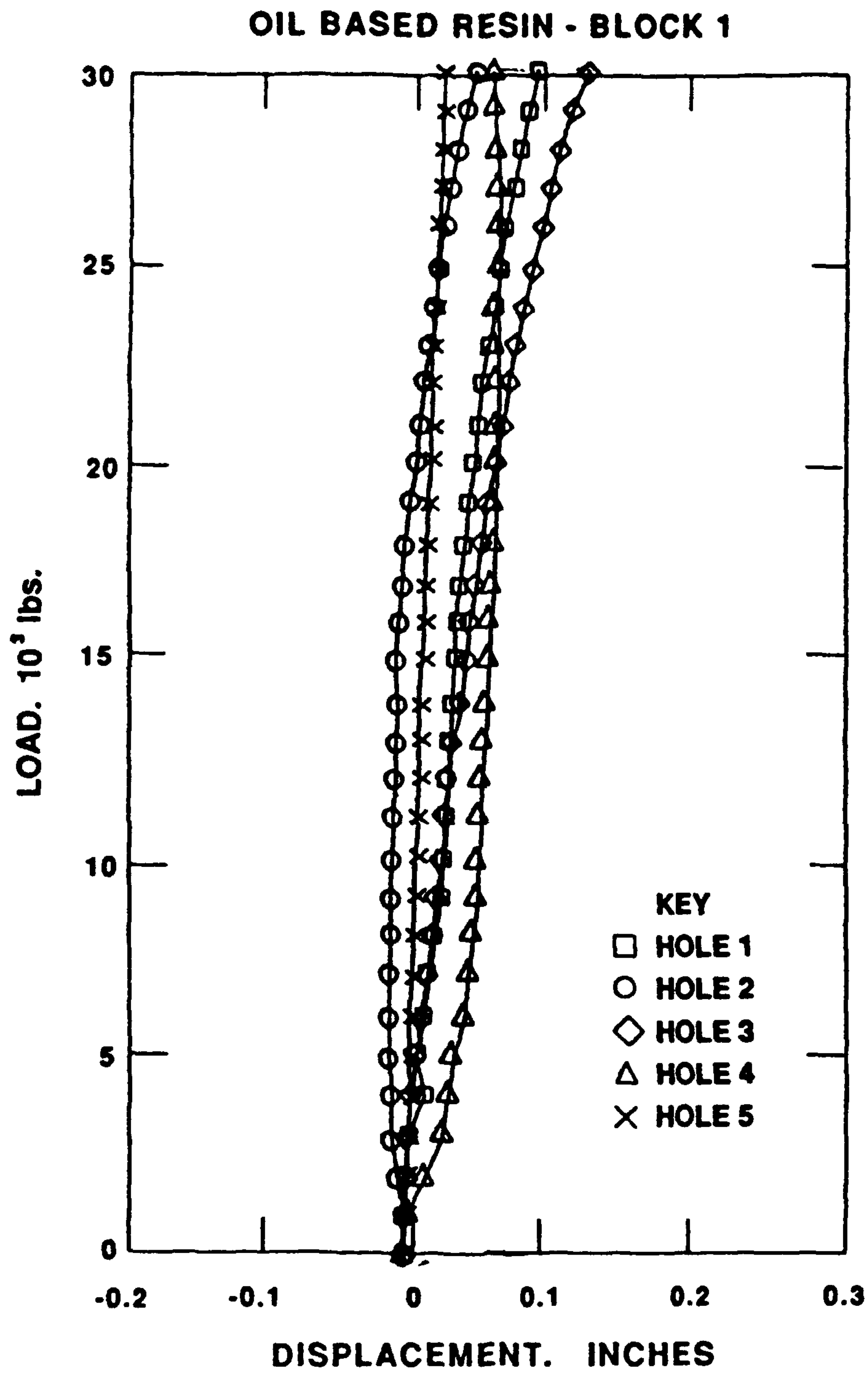

Figure A-1
Pull Test Bolt, Displacement versus Load

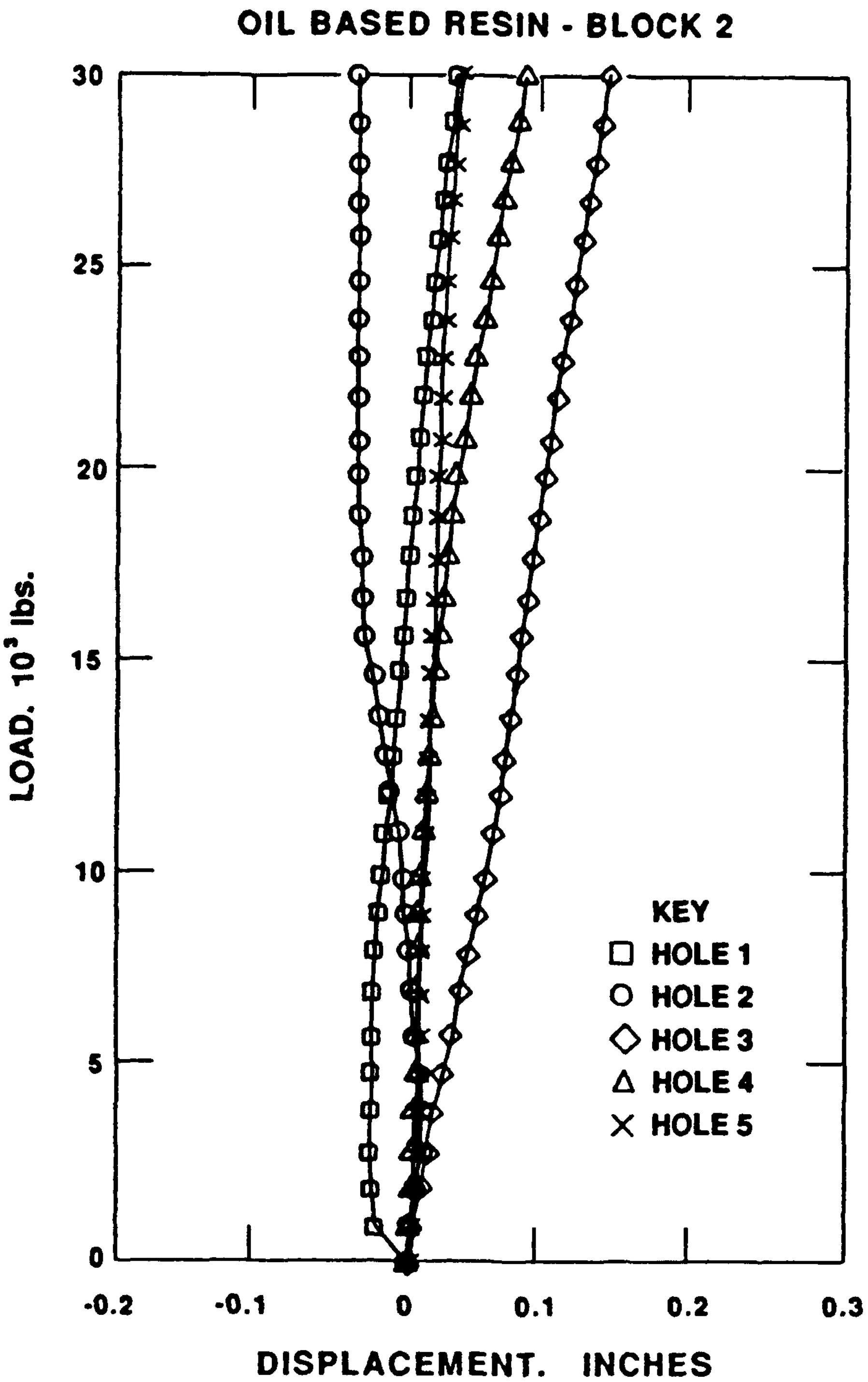

Figure A-2
Pull Test Bolt, Displacement versus Load

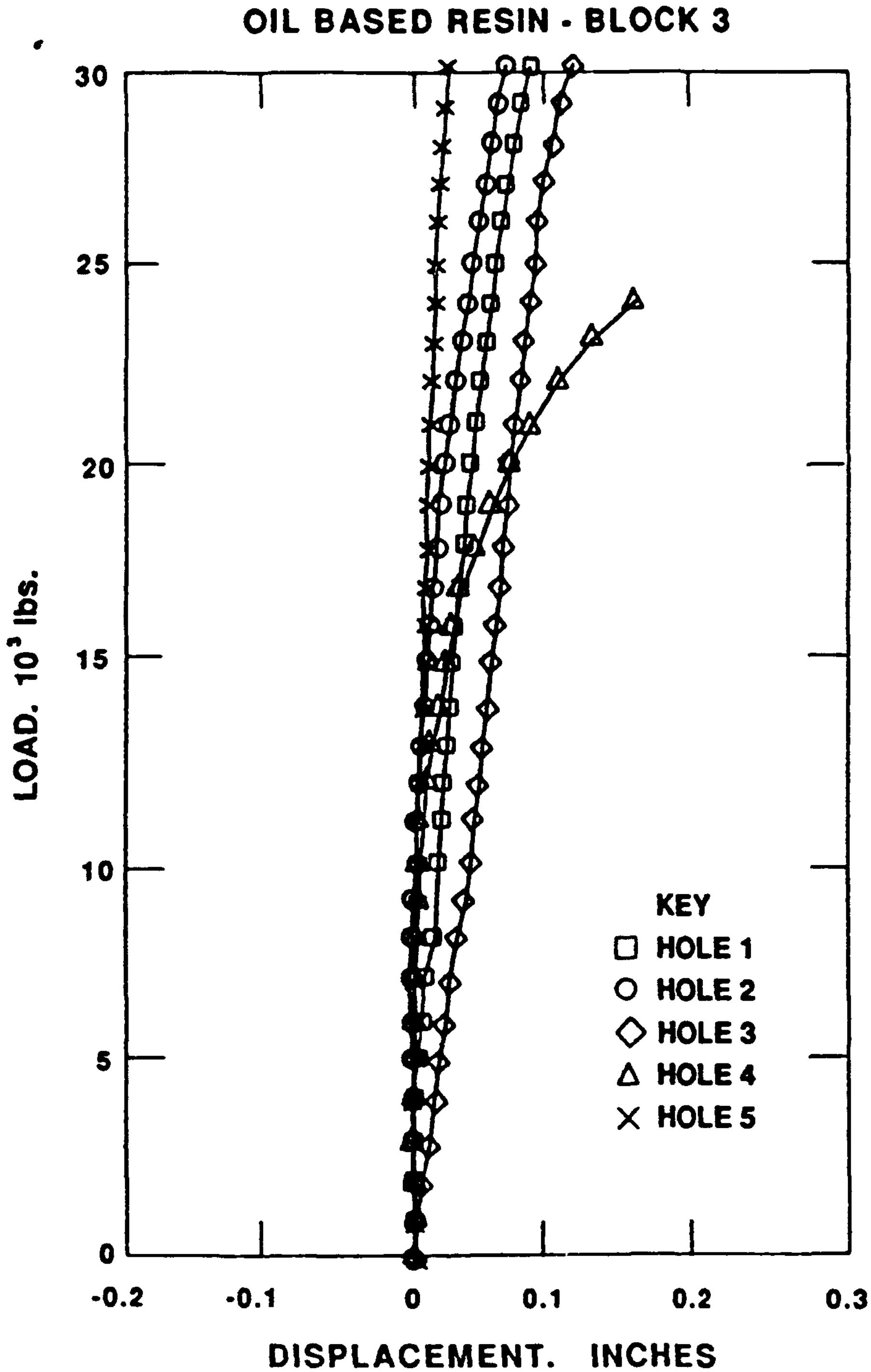

Figure A-3
Pull Test Bolt, Displacement versus Load

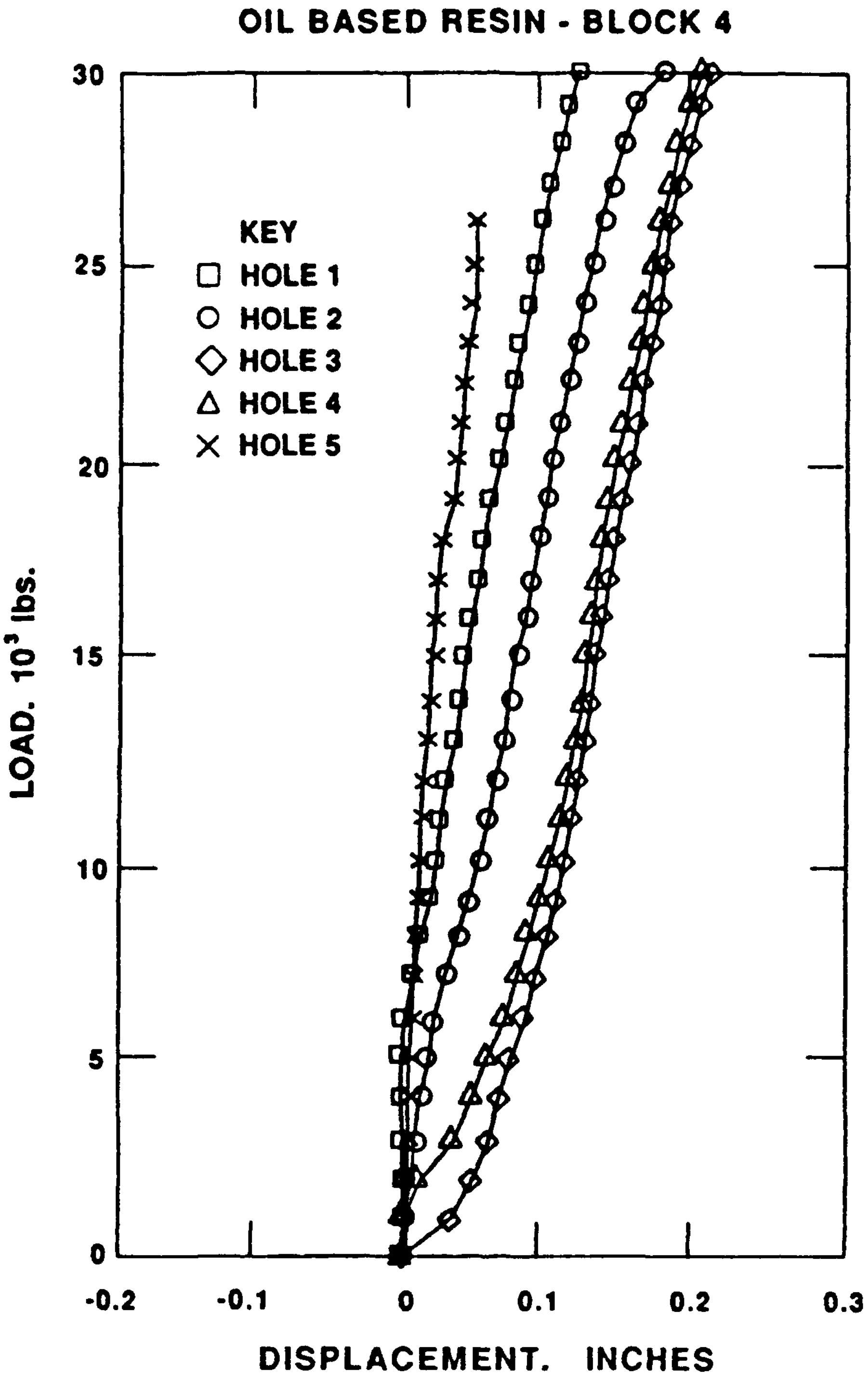

Figure A-4
Pull Test Bolt, Displacement versus Load

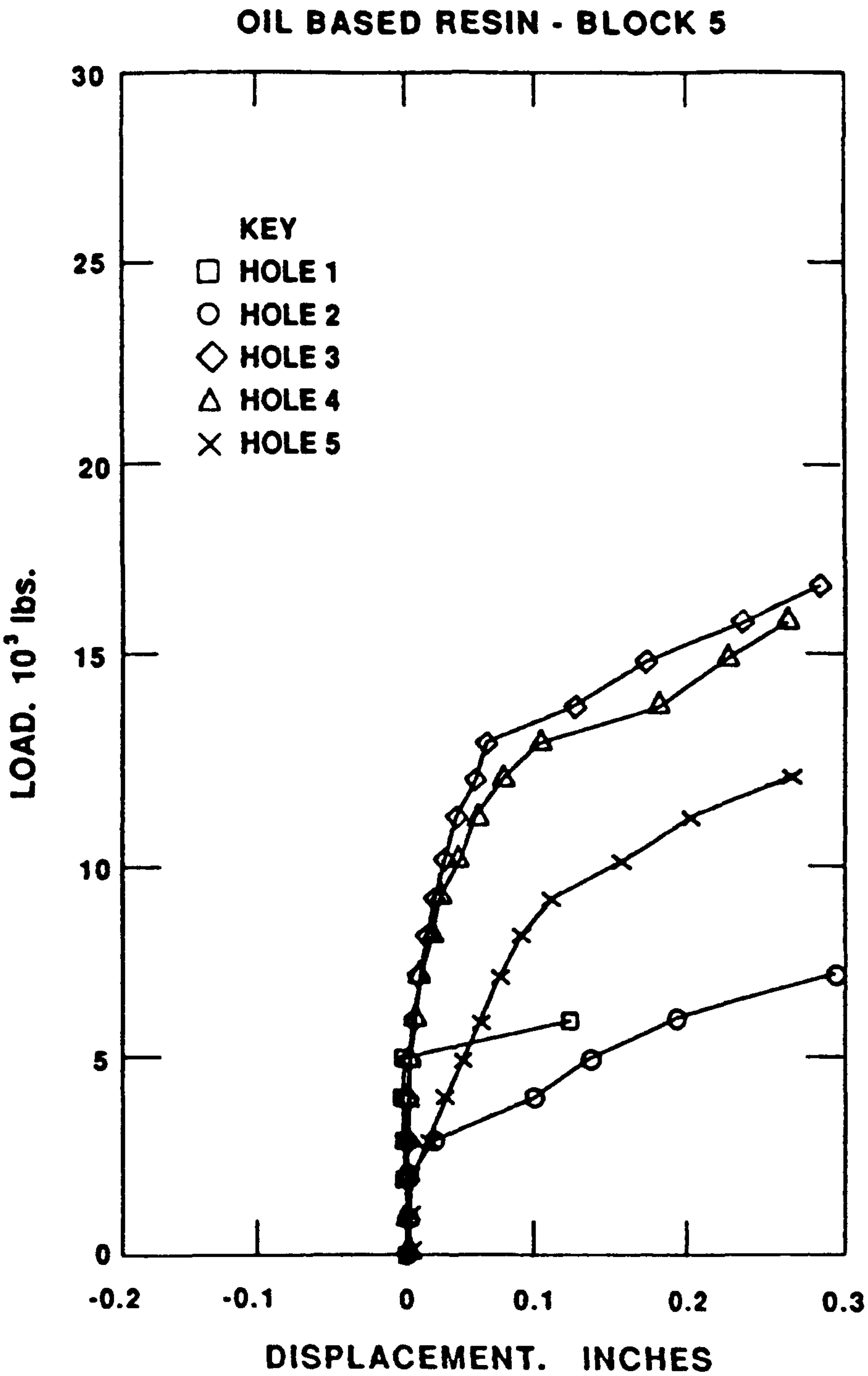

Figure A-5
Pull Test Bolt, Displacement versus Load

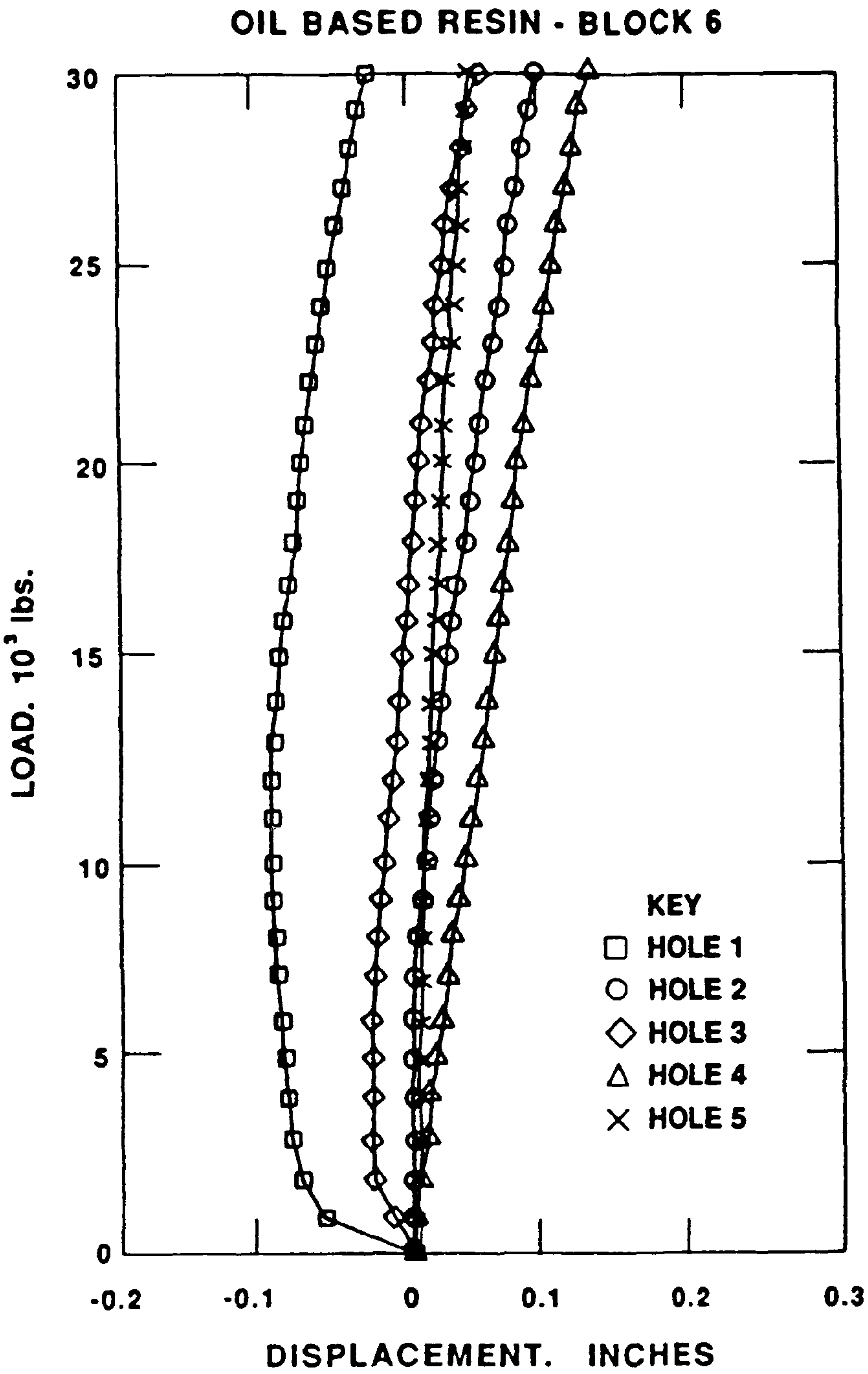

Figure A-6
Pull Test Bolt, Displacement versus Load

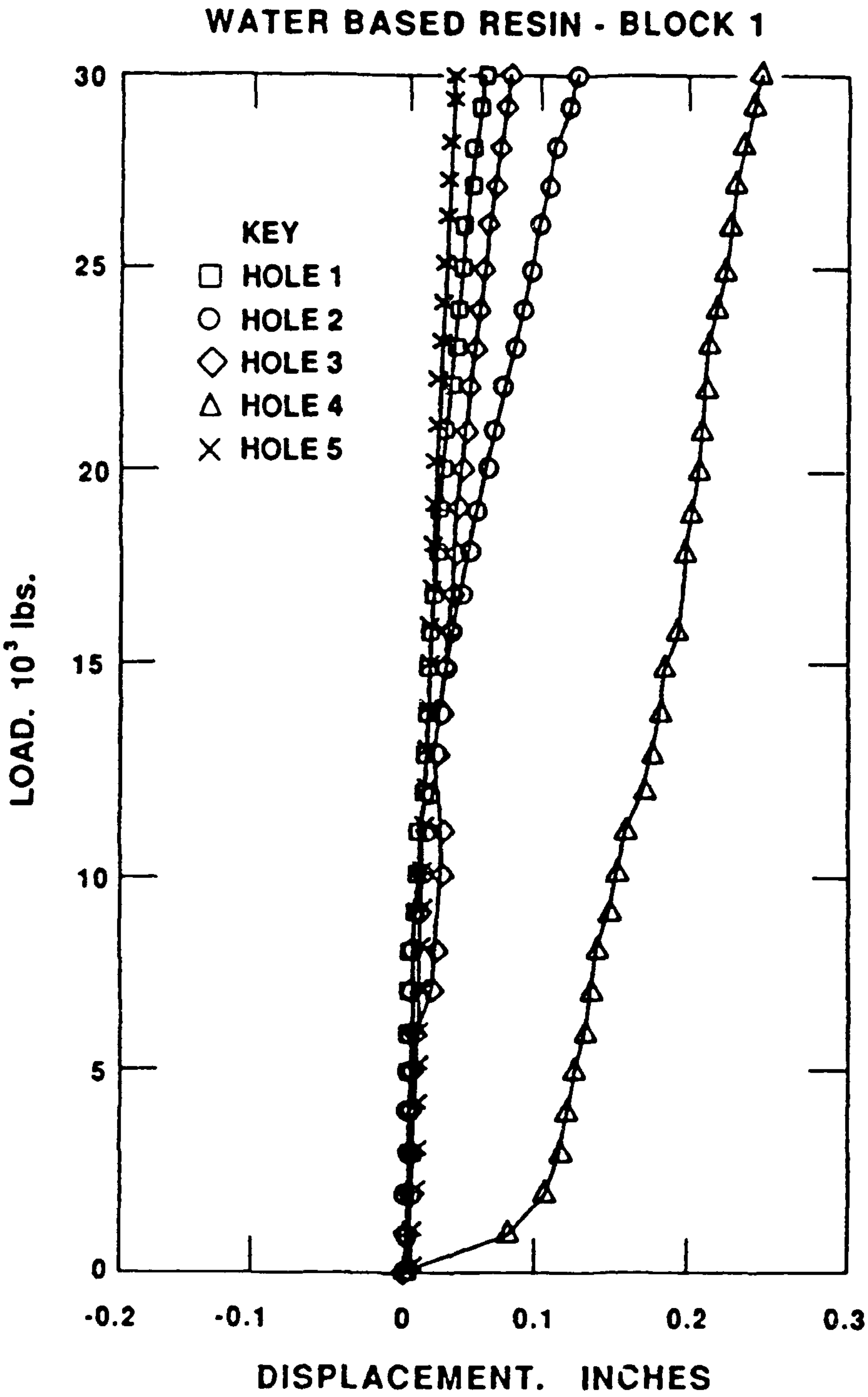

Figure A-7
Pull Test Bolt, Displacement versus Load

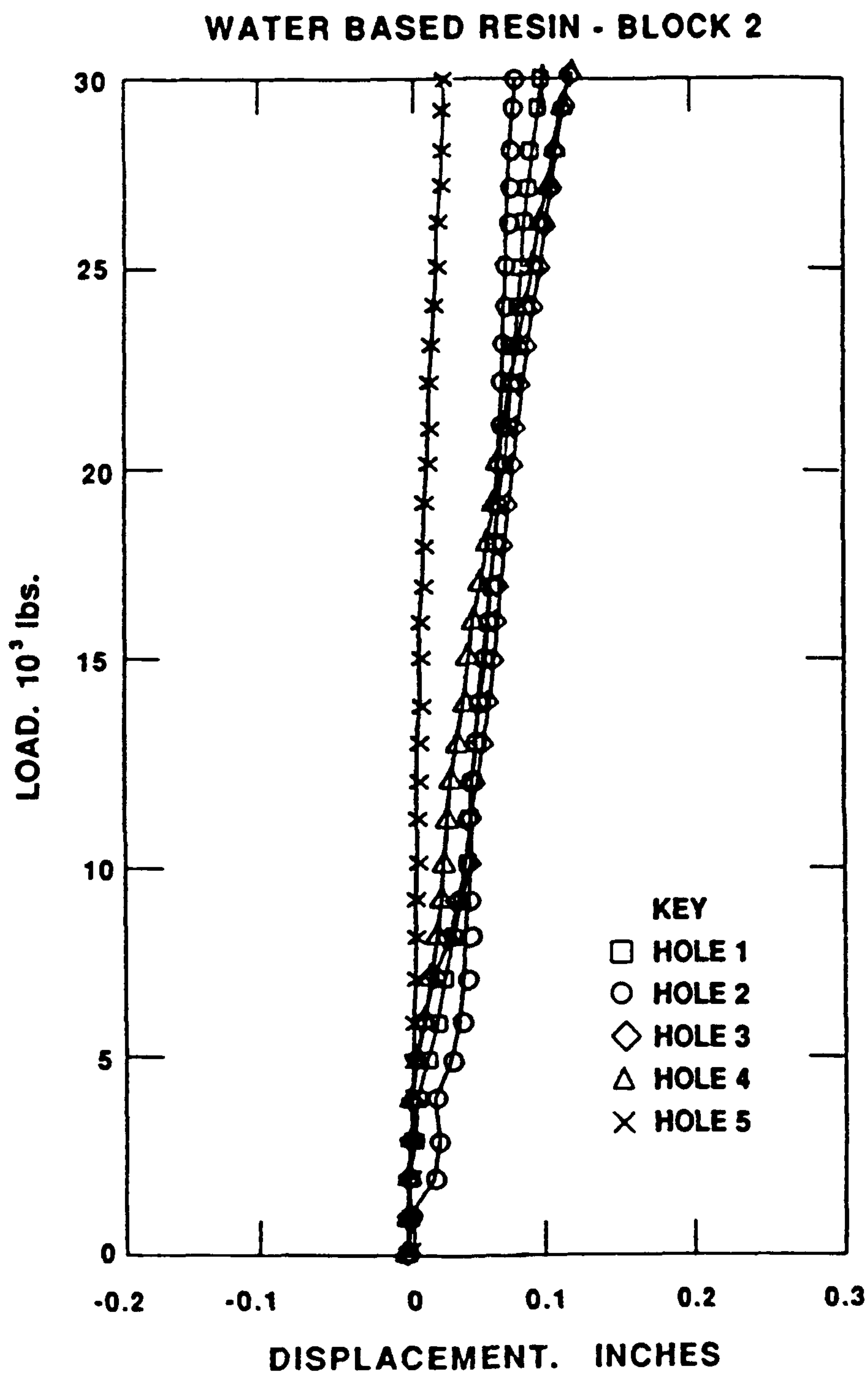

Figure A-8
Pull Test Bolt, Displacement versus Load

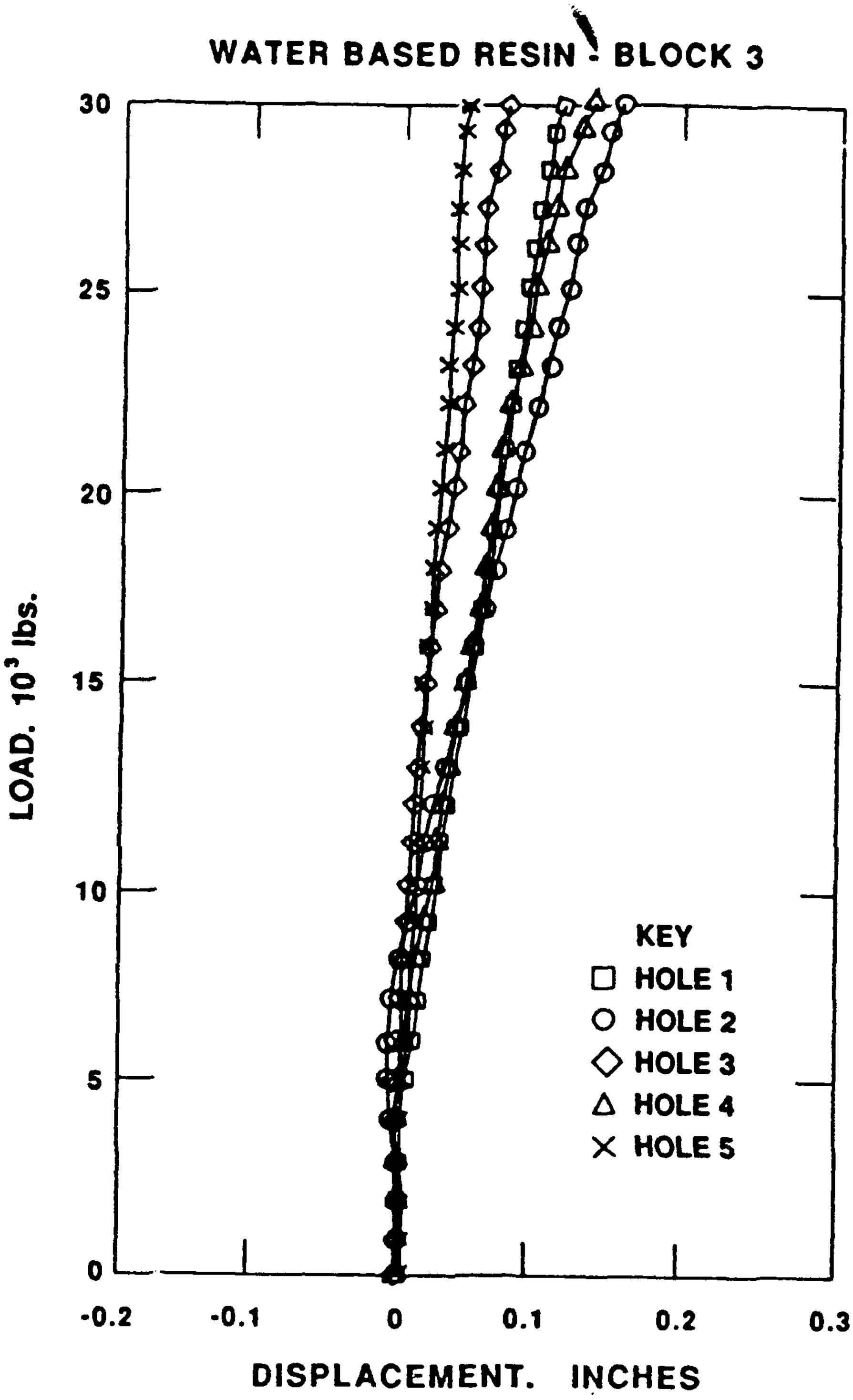

Figure A-9
Pull Test Bolt, Displacement versus Load

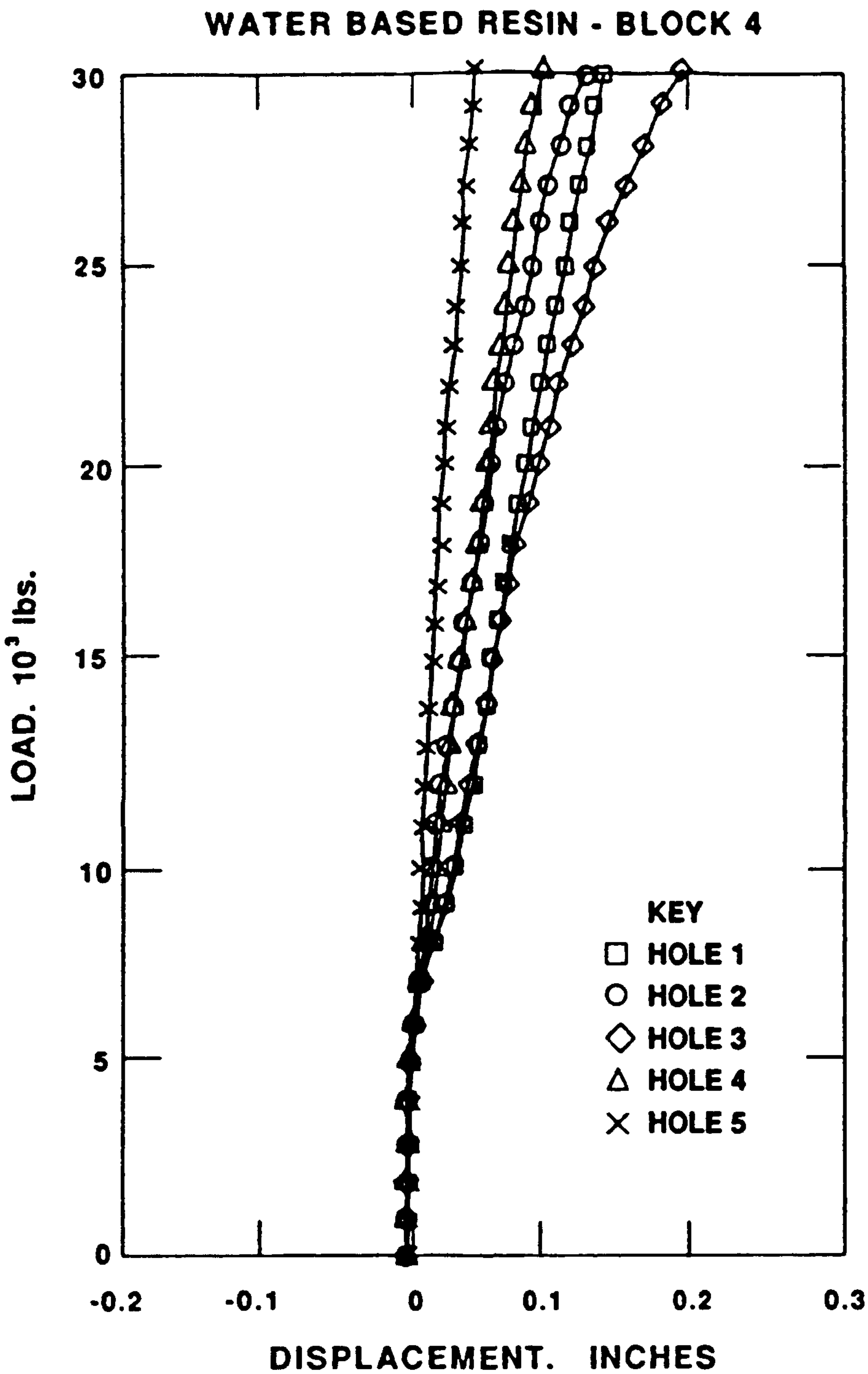

Figure A-10
Pull Test Bolt, Displacement versus Load

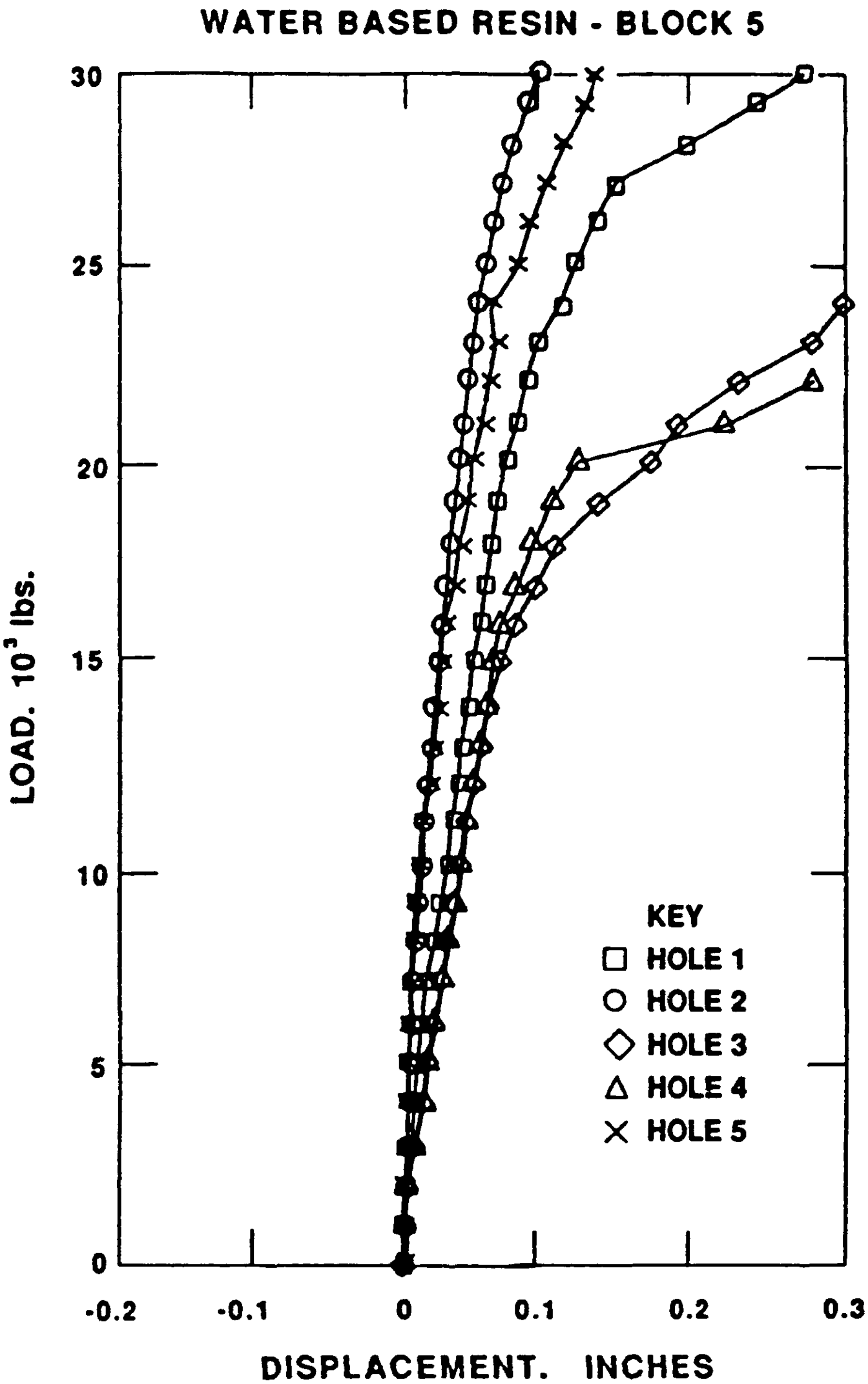

Figure A-11
Pull Test Bolt, Displacement versus Load

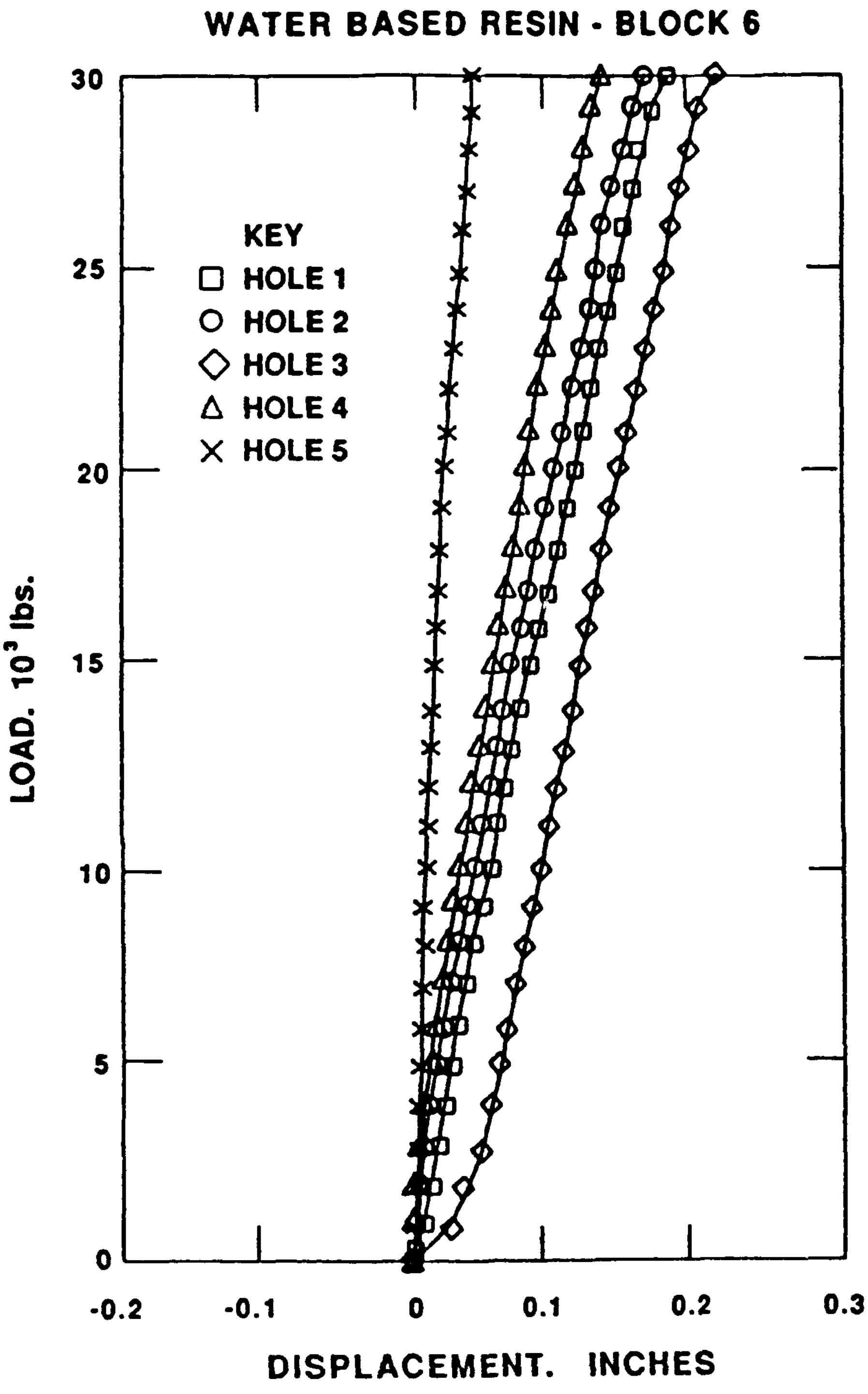

Figure A-12
Pull Test Bolt, Displacement versus Load

TABLE A-1. - Test data for oil-base resin, block 1 (dry), with 26-inch bolts

Force	Displacement Reading (Inches)				
	Extensometer				Ultrasonic
lb x 10^3	Hole #1	Hole #2	Hole #3	Hole #4	Hole #5
0	.000	.000	.000	.000	0
1	.000	.000	.000	.001	.0003
2	.001	-.006	.000	.013	.0008
3	.003	-.010	.013	.024	.0015
4	.005	-.011	.003	.027	.0020
5	.008	-.012	.006	.031	.0024
6	.012	-.012	.010	.037	.0027
7	.016	-.012	.014	.041	.0031
8	.019	-.012	.017	.043	.0034
9	.0235	-.012	.020	.047	.0039
10	.026	-.012	.023	.048	.0042
11	.027	-.012	.025	.049	.0046
12	.028	-.011	.028	.050	.0052
13	.029	-.011	.030	.051	.0055
14	.030	-.011	.034	.052	.0059
15	.031	-.012	.037	.053	.0065
16	.0315	-.010	.040	.055	.0070
17	.033	-.009	.043	.055	.0075
18	.035	-.007	.047	.056	.0082
19	.037	-.004	.050	.056	.0088
20	.040	-.001	.056	.056	.0095
21	.042	.001	.060	.056	.0101
22	.045	.004	.065	.056	.0109
23	.049	.008	.070	.056	.0116
24	.053	.011	.075	.056	.0123
25	.057	.015	.079	.056	.0131
26	.061	.018	.087	.056	.0137
27	.067	.022	.092	.056	.0146
28	.072	.028	.099	.054	.0155
29	.078	.032	.107	.053	.0164
30	.083	.039	.119	.052	.0176

TABLE A-2. - Test data for oil-base resin, block 2 (damp), with 26-inch bolts

	Displacement Reading (Inches)				
Force	Extensometer				Ultrasonic
lb x 10^3	Hole #1	Hole #2	Hole #3	Hole #4	Hole #5
0	.000	.000	.000	.000	0
1	-.0205	.000	.0005	.000	.0003
2	-.024	.001	.007	.0045	.0006
3	-.025	.0045	.0105	.005	.0010
4	-.025	.006	.015	.005	.0012
5	-.025	.007	.019	.005	.0017
6	-.025	.004	.025	.005	.0019
7	-.025	.000	.030	.005	.0023
8	-.025	-.0035	.035	.005	.0026
9	-.024	-.007	.040	.005	.0030
10	-.023	-.0095	.045	.005	.0033
11	-.021	-.013	.049	.055	.0037
12	-.020	-.017	.053	.007	.0039
13	-.018	-.022	.056	.008	.0043
14	-.016	-.027	.060	.010	.0047
15	-.014	-.033	.063	.011	.0050
16	-.012	-.037	.066	.013	.0056
17	-.010	-.040	.070	.015	.0061
18	-.0085	-.0415	.073	.018	.0067
19	-.007	-.043	.076	.020	.0071
20	-.005	-.044	.079	.0225	.0078
21	-.0035	-.045	.0825	.026	.0084
22	-.002	-.045	.086	.0295	.0090
23	.000	-.0455	.090	.033	.0096
24	.002	-.047	.094	.037	.0106
25	.0045	-.048	.098	.041	.0115
26	.007	-.048	.102	.045	.0127
27	.010	-.0485	.1065	.049	.0135
28	.0115	-.0485	.111	.055	.0149
29	.014	-.049	.115	.059	.0159
30	.018	-.050	.120	.064	N/R

N/R No reading

TABLE A-3. - Test data for oil-base resin, block 3 (wet), with 26-inch bolts

Force	Displacement Reading (Inches)				
	Extensometer				Ultrasonic
lb x 10³	Hole #1	Hole #2	Hole #3	Hole #4	Hole #5
0	.000	.000	.000	.000	0
1	.000	.000	.000	.000	.0001
2	.000	-.002	.004	.000	.0004
3	.000	-.003	.010	.000	.0009
4	.0005	-.003	.0135	.000	.0013
5	.003	-.003	.017	.000	.0016
6	.0065	-.003	.021	.0005	.0022
7	.010	-.002	.025	.0005	.0027
8	.0125	-.001	.0295	.0005	.0031
9	.016	.000	.034	.002	.0036
10	.0185	.002	.037	.004	.0042
11	.021	.003	.041	.007	.0048
12	.023	.005	.0435	.010	.0056
13	.0255	.0065	.047	.0135	.0063
14	.028	.009	.0505	.0185	.0070
15	.030	.011	.054	.024	.0081
16	.032	.0135	.057	.029	.0089
17	.0345	.016	.0615	.035	.0098
18	.037	.0185	.064	.045	.0107
19	.040	.021	.067	.057	.0115
20	.043	.024	.070	.070	.0126
21	.046	.027	.073	.084	.0137
22	.049	.0305	.077	.105	.0146
23	.052	.034	.080	.130	.0153
24	.0565	.039	.083	.160	.0168
25	.0595	.043	.087	F	.0179
26	.0645	.047	.089		.0190
27	.070	.052	.095		.0203
28	.0745	.057	.1005		.0218
29	.080	.0625	.106		.0236
30	.0875	.0685	.116		.0279

F No readings because of failure of the grout

TABLE A-4. - Test data for oil-base resin, block 4 (submerged), with 29-inch bolts

Force	Displacement Reading (Inches)				
	Extensometer				Ultrasonic
lb x 10^3	Hole #1	Hole #2	Hole #3	Hole #4	Hole #5
0	.000	.000	.000	.000	0
1	.000	.000	.032	.000	.0005
2	.000	.000	.044	.009	.0012
3	.000	.007	.056	.0315	.0023
4	.000	.012	.0635	.0435	.0035
5	.000	.016	.071	.054	.0046
6	.000	.0215	.0815	.0665	.0059
7	.006	.028	.089	.0755	.0065
8	.011	.036	.0955	.083	.0077
9	.017	.043	.102	.0915	.0087
10	.021	.0495	.107	.098	.0097
11	.024	.055	.112	.104	.0110
12	.027	.061	.117	.1095	.0120
13	.032	.0655	.122	.1135	.0136
14	.036	.0705	.1265	.119	.0152
15	.039	.075	.131	.122	.0168
16	.043	.0805	.135	.126	.0187
17	.047	.085	.139	.1295	.0200
18	.051	.0895	.143	.1335	.0222
19	.056	.094	.1475	.138	.0303
20	.062	.0985	.1525	.143	.0320
21	.067	.103	.157	.147	.0335
22	.072	.109	.1615	.152	.0354
23	.0765	.114	.1665	.157	.0377
24	.081	.1195	.171	.161	.0395
25	.086	.1255	.175	.1665	.0412
26	.0915	.132	.180	.172	.0428
27	.0965	.139	.185	.1795	N/R
28	.103	.146	.192	.185	N/R
29	.109	.154	.199	.193	N/R
30	.117	.174	.208	.2015	N/R

N/R No reading

TABLE A-5. - Test data for oil-base resin, block 5 (submerged), with 17-inch bolts

Force lb x 10³	Displacement Reading (Inches) Extensometer Hole #1	Hole #2	Hole #3	Hole #4	Hole #5
0	.000	.000	.000	.000	.000
1	.000	.000	.000	.000	.000
2	.000	-.002	.004	.000	.000
3	-.004	.018	.002	.0005	.011
4	-.0005	.090	.002	.001	.024
5	.002	.130	.003	.0025	.036
6	.115	.190	.006	.006	.049
7	F	.30	.0095	.010	.063
8		.45	.014	.017	.080
9		F	.019	.025	.100
10			.026	.036	.150
11			.035	.050	.200
12			.048	.070	.200
13			.058	.095	.270
14			.120	.180	.320
15			.170	.230	.460
16			.240	.270	F
17			.290	.340	
18			.350	.340	
19			.440	.460	
20			F	F	
21					
22					
23					
24					
25					
26					
27					
28					
29					
30					

F No readings because of failure of the grout

TABLE A-6. - Test data for oil-base resin, block 6 (submerged), with 38-inch bolts

Force	Displacement Reading (Inches)				
	Extensometer				Ultrasonic
lb x 10^3	Hole #1	Hole #2	Hole #3	Hole #4	Hole #5
0	.000	.000	.000	.000	0
1	-.0585	.000	-.014	.0005	.0007
2	-.075	.000	-.027	.005	.0014
3	-.082	.000	-.027	.009	.0023
4	-.084	.000	-.027	.0115	.0030
5	-.0855	.000	-.027	.015	.0038
6	-.088	.000	-.027	.0185	.0045
7	-.090	.000	-.0255	.022	.0050
8	-.0915	.003	-.024	.0265	.0058
9	-.092	.0055	-.022	.0305	.0066
10	-.0925	.0085	-.0195	.035	.0074
11	-.0925	.011	-.0175	.039	.0082
12	-.0925	.0135	-.015	.0425	.0089
13	-.0925	.017	-.013	.047	.0097
14	-.091	.020	-.0105	.050	.0101
15	-.089	.023	-.0085	.054	.0116
16	-.087	.026	-.006	.057	.0128
17	-.084	.0295	-.004	.061	.0141
18	-.0815	.0335	-.002	.064	.0153
19	-.0785	.037	-.0005	.068	.0168
20	-.075	.0405	.0025	.071	.0181
21	-.072	.044	.005	.076	.0191
22	-.0685	.0475	.0085	.080	.0200
23	-.065	.052	.012	.0835	.0222
24	-.060	.057	.015	.089	.0234
25	-.057	.061	.018	.093	.0257
26	-.053	.065	.021	.0975	.0274
27	-.048	.069	.024	.1025	.0292
28	-.043	.074	.0285	.108	.0304
29	-.037	.079	.035	.113	.0332
30	-.0315	.084	.042	.119	.0352

TABLE A-7. - Test data for water-base resin, block 1 (dry), with 26-inch bolts

Force	Displacement Reading (Inches)				
	Extensometer				Ultrasonic
lb x 10³	Hole #1	Hole #2	Hole #3	Hole #4	Hole #5
0	.000	.000	.000	.000	0
1	.000	.000	.000	.071	.0007
2	.000	.000	.004	.094	.0013
3	-.001	.001	.005	.104	.0019
4	-.001	.001	.005	.110	.0023
5	-.001	.002	.006	.115	.0026
6	-.001	.002	.006	.121	.0031
7	.000	.003	.017	.125	.0034
8	.000	.004	.019	.130	.0038
9	.002	.006	N/R	.137	.0041
10	.002	.010	.021	.143	.0045
11	.004	.012	.022	.147	.0049
12	.006	.015	N/R	.160	.0053
13	.008	.018	N/R	.166	.0059
14	.009	.021	.022	.171	.0064
15	.011	.025	.022	.175	.0069
16	.011	.028	.024	.182	.0076
17	.012	.031	.026	N/R	.0083
18	.014	.037	.028	.188	.0090
19	.0155	.043	.030	.192	.0098
20	.018	.049	.032	.196	.0105
21	.020	.055	.034	.199	.0113
22	.022	.061	.0365	.2025	.0121
23	.024	.067	.039	.205	.0130
24	.026	.073	.041	.210	.0139
25	.028	.078	.044	.216	.0148
26	.030	.084	.047	.2195	.0157
27	.032	.090	.052	.223	.0169
28	.035	.095	.056	.228	.0180
29	.039	.103	.060	.234	.0193
30	.046	.109	.065	.241	.0205

N/R No reading

TABLE A-8. - Test data for water-base resin, block 2 (damp), with 26-inch bolts

Force lb x 10^3	Displacement Reading (Inches)				
	Extensometer				Ultrasonic
	Hole #1	Hole #2	Hole #3	Hole #4	Hole #5
0	.000	.000	.000	.000	0
1	.000	.005	.000	.000	.0004
2	.000	.0175	.000	.002	.0009
3	.0005	.0215	.000	.005	.0015
4	.007	.0200	.002	.005	.0022
5	.0135	.030	.006	.005	.0028
6	.021	.034	.013	.0085	.0032
7	.0265	.037	.020	.0135	.0037
8	.032	.0385	.027	.0185	.0041
9	.0365	.041	.0335	.022	.0048
10	.039	.044	.039	.0245	.0052
11	.041	.0455	.044	.027	.0056
12	.043	.048	.048	.030	.0061
13	.0455	.050	.0525	.033	.0066
14	.048	.0515	.056	.0375	.0069
15	.051	.0553	.0595	.041	.0075
16	.0525	.0555	.062	.045	.0082
17	.0555	.0575	.065	.0495	.0088
18	.058	.0590	.068	.0535	.0101
19	.060	.0610	.071	.058	.0113
20	.064	.0630	.075	.063	.0125
21	.067	.0640	.078	.068	.0135
22	.0695	.0660	.081	.0725	.0148
23	.072	.0670	.0845	.078	.0159
24	.076	.0680	.088	.0825	.0172
25	.0785	.0695	.092	.088	.0185
26	.0815	.071	.097	.093	.0203
27	.085	.0725	.1025	.099	.0219
28	.088	.074	.106	.1045	.0234
29	.092	.076	.111	.1095	.0252
30	.095	.077	.116	.117	.0269

TABLE A-9. - Test data for water-base resin, block 3 (wet), with 26-inch bolts

Force lb x 10³	Displacement Reading (Inches)				
	Extensometer				Ultrasonic
	Hole #1	Hole #2	Hole #3	Hole #4	Hole #5
0	.000	.000	.000	.000	0
1	.000	.000	.000	.000	.0000
2	.000	.000	.000	.000	.0003
3	.000	-.0025	-.001	.000	.0012
4	.0015	-.006	-.006	.000	.0021
5	.0045	-.007	.000	.000	.0031
6	.009	-.007	.001	.002	.0039
7	.0125	-.005	.0025	.007	.0050
8	.0165	.000	.0035	.012	.0060
9	.0210	.006	.005	.0175	.0072
10	.024	.012	.006	.022	.0083
11	.028	.018	.0085	.0265	.0094
12	.0315	.024	.010	.031	.0107
13	.036	.0305	.0125	.035	.0122
14	.0405	.037	.015	.0395	.0137
15	.0445	.046	.0175	.045	.0150
16	.048	.051	.020	.050	.0163
17	.053	.058	.023	.054	.0178
18	.057	.065	.026	.058	.0195
19	.062	.072	.0295	.062	.0211
20	.0665	.080	.0335	.0675	.0228
21	.070	.085	.037	.0715	.0242
22	.074	.093	.040	.0765	.0259
23	.078	.100	.044	.082	.0276
24	.083	.106	.0485	.087	.0294
25	.086	.114	.0515	.092	.0309
26	.090	.121	.055	.0975	.0326
27	.095	.1275	.0560	.106	.0344
28	.099	.138	.0635	.113	.0359
29	.103	.145	.068	.125	.0380
30	.109	.155	.073	.135	.0411

TABLE A-10. - Test data for water-base resin, block 4 (submerged), with 29-inch bolts

Force lb x 10³	Displacement Reading (Inches)				
	Extensometer				Ultrasonic
	Hole #1	Hole #2	Hole #3	Hole #4	Hole #5
0	.000	.000	.000	.000	0
1	.000	.000	.000	.000	.0000
2	.000	.000	.000	.000	.0002
3	.000	.0005	.000	.000	.0017
4	.000	.0005	.000	.000	.0027
5	.000	.0005	.000	.004	.0040
6	.0025	.003	.0025	.008	.0052
7	.011	.007	.0010	.0115	.0065
8	.019	.011	.0018	.015	.0076
9	.028	.014	.025	.0185	.0085
10	.0345	.0185	.0305	.0225	.0102
11	.040	.0215	.036	.0255	.0115
12	.046	.025	.042	.029	.0127
13	.050	.030	.048	.032	.0140
14	.0555	.033	.0555	.035	.0156
15	.060	.0375	.0615	.039	.0170
16	.0645	.0415	.068	.042	.0185
17	.070	.0465	.0725	.046	.0202
18	.074	.0505	.078	.049	.0218
19	.0785	.056	.086	.052	.0237
20	.084	.060	.094	.0555	.0259
21	.089	.065	.101	.059	.0277
22	.094	.070	.108	.0615	.0297
23	.100	.076	.116	.066	.0319
24	.105	.082	.126	.070	.0339
25	.1115	.087	.133	.073	.0365
26	.116	.094	.1435	.076	.0384
27	.1225	.100	.154	.0815	.0399
28	.1285	.109	.167	.086	.0432
29	.134	.117	.179	.0915	.0461
30	.141	.131	.196	.100	.0487

TABLE A-11. - Test data for water-base resin, block 5 (submerged), with 17-inch bolts

Force lb x 10^3	Displacement Reading (Inches) Extensometer Hole #1	Hole #2	Hole #3	Hole #4	Hole #5
0	.000	.000	.000	.000	.000
1	.000	.000	.000	.001	.000
2	.000	.000	.000	.003	.0005
3	.0005	.000	.006	.006	.0005
4	.004	.000	.0115	.012	.0005
5	.007	.000	.0145	.015	.0005
6	.010	.002	.017	.020	.0005
7	.0135	.004	.021	.024	.0005
8	.0175	.006	.025	.028	.003
9	.021	.009	.030	.032	.005
10	.0255	.011	.034	.036	.007
11	.0285	.013	.0375	.039	.010
12	.032	.015	.043	.044	.0145
13	.035	.017	.050	.050	.016
14	.039	.0195	.055	.052	.020
15	.0425	.0215	.063	.057	.023
16	.047	.023	.073	.063	.025
17	.051	.026	.086	.073	.030
18	.055	.028	.100	.083	.033
19	.060	.030	.130	.096	.037
20	.065	.032	.165	.112	.041
21	.071	.035	.185	.220	.046
22	.078	.038	.230	.280	.051
23	.085	.041	.280	.350	.056
24	.100	.045	.306	.600	.063
25	.110	.050	.355	F	.070
26	.125	.054	.370		.078
27	.140	.061	.400		.088
28	.190	.068	.600		.010
29	.240	.077	F		.115
30	.280	.085			.125

F No readings because of failure of the grout

TABLE A-12. - Test data for water-base resin, block 6 (submerged), with 38-inch bolts

Force	Displacement Reading (Inches)				
	Extensometer				Ultrasonic
lb x 10^3	Hole #1	Hole #2	Hole #3	Hole #4	Hole #5
0	.000	.000	.000	.000	0
1	.007	.000	.0255	.000	.0000
2	.0125	.0035	.035	.000	.0008
3	.017	.0075	.0455	.002	.0020
4	.022	.011	.0525	.006	.0027
5	.0255	.016	.058	.010	.0035
6	.030	.021	.065	.015	.0043
7	.035	.0255	.071	.019	.0051
8	.040	.0305	.078	.023	.0059
9	.0465	.0365	.084	.028	.0066
10	.052	.041	.090	.0315	.0074
11	.0575	.046	.0955	.036	.0085
12	.063	.052	.101	.040	.0092
13	.068	.057	.1065	.044	.0103
14	.074	.062	.112	.0485	.0112
15	.0815	.0675	.117	.0535	.0124
16	.0875	.0735	.122	.057	.0136
17	.0945	.0795	.128	.062	.0149
18	.1005	.0845	.133	.067	.0163
19	.1065	.091	.139	.072	.0177
20	.112	.097	.146	.0765	.0189
21	.1175	.1025	.151	.080	.0210
22	.1245	.109	.158	.0845	.0228
23	.130	.1155	.163	.090	.0243
24	.1365	.122	.170	.095	.0265
25	.1425	.128	.177	.100	.0285
26	.148	.133	.183	.1055	.0305
27	.1535	.140	.189	.1125	.0340
28	.160	.147	.1955	.118	.0345
29	.168	.154	.2025	.124	.0368
30	.178	.162	.2155	.1325	.0395

TABLE A13
DRILL HOLE DATA (INCHES)
OIL BASE RESIN

	Hole Depth	Hole Diameters Top*	Middle	Bottom**
Block #1				
Hole #1	26	N/A	N/A	N/A
2	26 3/8	N/A	N/A	N/A
3	26 1/4	N/A	N/A	N/A
4	26	N/A	N/A	N/A
5	26 1/4	1 1/16	1 1/16	1
Block #2				
Hole #1	26	1 1/16	1 1/16	1
2	26	1 1/16	1 1/16	1 1/16
3	26	1 1/16	1 3/16	1
4	25 3/4	1 1/16	1 1/8	1 1/16
5	26	1 1/16	1 1/16	1 1/16
Block #3				
Hole #1	26	1 1/16	1 5/32	1
2	26 1/4	1 1/16	1 1/16	1 1/16
3	26 1/4	1 1/8	1 1/16	1 1/16
4	26	1 1/8	1 1/8	1 1/8
5	25 7/8	1 1/8	1 1/16	1 1/6
Block #4				
Hole #1	29	1 1/32	1 1/16	1 1/8
2	28 3/4	1 1/8	1 1/8	1 1/8
3	28 3/4	1 1/16	1 3/16	1 1/8
4	29	1 1/8	1 3/32	1 1/16
5	29	1 1/16	1 1/8	1 1/8
Block #5				
Hole #1	17	1 1/8	1 1/16	1
2	16 7/8	1 5/32	1 1/16	1 5/32
3	16 3/4	1 1/8	1 3/16	1 1/32
4	17	1 1/16	1 1/8	1
5	17	1 1/8	1 1/8	1
Block #6				
Hole #1	38 1/2	1 1/16	1	1
2	38 1/2	1 1/16	1	1
3	38 3/4	1 1/16	1 1/16	1 1/16
4	38 1/2	1 1/16	1 1/16	1 1/16
5	38 1/2	1	1	1 5/16

* Measured 6" down from collar of hole
** Measured 2" up from bottom of hole
N/A Not Available

TABLE A14
DRILL HOLE DATA (INCHES)
WATER BASE RESIN

	Hole Depth	Hole Diameters Top*	Middle	Bottom**
Block #1				
Hole #1	26	N/A	N/A	N/A
2	26	N/A	N/A	N/A
3	26	N/A	N/A	N/A
4	25 5/8	N/A	N/A	N/A
5	25 3/4	1 1/8	1 1/8	1 1/16
Block #2				
Hole #1	25 3/4	1 1/8	1 1/8	1 1/8
2	26	1 1/16	1 1/16	1 1/16
3	26	1	1	1
4	26	1 1/16	1 1/8	1 1/16
5	26 1/4	1 1/8	1 3/32	1 1/16
Block #3				
Hole #1	26	1 1/16	1 1/8	1
2	26	1 1/16	1 1/8	1
3	26	1 1/16	1 1/16	1 1/16
4	26	1 1/4	1 1/16	1 1/16
5	26	1 1/8	1 1/8	1
Block #4				
Hole #1	28 3/4	1 1/16	1 1/16	1
2	29	1 1/8	1 1/8	1 1/16
3	29	1 1/8	1 1/8	1 1/8
4	29	1 1/8	1 1/8	1 1/8
5	28 3/4	1 1/8	1 1/8	1 1/16
Block #5				
Hole #1	17	1 1/16	1 1/16	1
2	16 1/2	1 1/8	1 1/16	1 1/16
3	16 3/4	1 1/8	1	1
4	17	1 1/16	1 1/16	1 1/16
5	17	1 1/8	1 1/16	1
Block #6				
Hole #1	38 1/2	1 1/8	1 1/8	15/16
2	39	1 1/16	1 1/16	1 1/16
3	38 3/4	1 1/8	1 1/16	1 1/16
4	38 3/4	1 1/16	1 1/16	1 1/16
5	38 3/4	1 1/8	1 1/8	1 1/16

* Measured 6" down from collar of hole
** Measured 2" up from bottom of hole
N/A Not Available

TABLE A15
BOLT INSTALLATION DATA
OIL-BASE RESIN

	Tube Length Inches	Comments: Resin	Comments: Water
Block #1			
Hole #1	24	Some overflow	Dry
2	24	Slight overflow	Dry
3	24	Slight overflow	Dry
4	24	Some overflow	Dry
5	24	Some overflow	Dry
Block #2			
Hole #1	24	Some overflow	Damp
2	24	Some overflow	Damp
3	24	Some overflow	Damp
4	24	Some overflow	Damp
5	24	Some overflow	Damp
Block #3			
Hole #1	24	Some overflow	Water forced out
2	24	Some overflow	Water forced out
3	24	Some overflow	Water forced out
4	24	Some overflow	Water forced out
5	24	Some overflow	Water forced out
Block #4			
Hole #1	24	Some overflow	Water forced out
2	21	Some overflow	Water forced out
3	18	No overflow	Water present
4	18	No overflow	Water present
5	18	No overflow	Water present
Block #5			
Hole #1	9.5	No overflow	Water present
2	9.5	No overflow	Water present
3	9.5	No overflow	Water present
4	9.5	No overflow	Water present
5	9.5	No overflow	Water present
Block #6			
Hole #1	30	Some overflow	Water forced out
2	30	Some overflow	Water forced out
3	30	Some overflow	Water forced out
4	30	Some overflow	Water forced out
5	30	Some overflow	Water forced out

TABLE A16
BOLT INSTALLATION DATA
WATER-BASE RESIN

	Tube Length Inches	Comments	
		Resin	Water
Block #1			
Hole #1	17	No overflow	Dry
2	21	Some overflow	Dry
3	21	Slight overflow	Dry
4	21	Some overflow	Dry
5	21	Slight overflow	Dry
Block #2			
Hole #1	21	No overflow	Damp
2	22	Slight overflow	Damp
3	22	Slight overflow	Damp
4	22	Slight overflow	Damp
5	21	Slight overflow	Damp
Block #3			
Hole #1	22	Some overflow	Water forced out
2	22	Some overflow	Water forced out
3	21	Slight overflow	Water forced out
4	21	Slight overflow	Water forced out
5	21	Some overflow	Water forced out
Block #4			
Hole #1	21	Slight overflow	Water forced out
2	17	No overflow	Water present
3	17	No overflow	Water present
4	19	No overflow	Water present
5	17	No overflow	Water present
Block #5			
Hole #1	9.5	No overflow	Water present
2	9.5	No overflow	Water present
3	9.5	No overflow	Water present
4	9.5	No overflow	Water present
5	9.5	No overflow	Water present
Block #6			
Hole #1	25.5	No overflow	Water present
2	25.5	No overflow	Water present
3	25.5	No overflow	Water present
4	25.5	No overflow	Water present
5	25.5	No overflow	Water present

APPENDIX B

TO

Report F 7891

Rockbolt Pull Test Data

from

Bonneville Locks

Table B-1

Bonneville Series 1 Test Results

Control Series

Hole Number	Hole Diameter	Hole Depth	Grout Length	Water Condition	Max Load Pounds	Strength Per Inch
1-1	2-1/4"	8'	24"	Dry	118,000	4,917
1-2	2-1/4"	8'	25"	Dry	108,000	4,320
1-3	2-1/4"	8'	25"	Dry	69,000	2,760
1-4	2-1/4"	8'	44.5"	Dry	198,000	4,449
1-5	2-1/4"	8'	50.5"	Dry	198,000	3,921
1-6	2-1/4"	8'	52"	Dry	179,000	3,442
1-7	2-1/4"	8'	78"	Dry	88,000	1,128
1-8	2-1/4"	8'	84"	Dry	209,000	2,488
1-9	2-1/4"	8'	85"	Dry	188,000	2,211
1-10	2-1/4"	8'	96"	Dry	165,000	1,718
1-11	2-1/4"	8'	96"	Dry	183,000	1,906
1-12	2-1/4"	8'	96"	Dry	206,000	2,145

Table B-2

Bonneville Series 2 Test Results

Submerged Comparison

Hole Number	Hole Diameter	Hole Depth	Grout Length	Water Condition	Max Load Pounds	Strength Per Inch
2-1	2-1/4"	8'	24"	Wet	102,434	4,268
2-2	2-1/4"	8'	25"	Wet	86,178	3,447
2-3	2-1/4"	8'	30"	Wet	68,097	2,269
2-4	2-1/4"	8'	51"	Wet	140,250	2,750
2-5	2-1/4"	8'	58.5"	Wet	99,970	1,708
2-6	2-1/4"	8'	36"	Wet	196,748	5,465
2-7	2-1/4"	8'	83"	Wet	217,611	2,651
2-8	2-1/4"	8'	75"	Wet	206,348	2,751
2-9	2-1/4"	8'	74"	Wet	213,254	2,881
2-10	2-1/4"	8'	96"	Wet	201,337	2,097
2-11	2-1/4"	8'	96"	Wet	215,902	2,248
2-12	2-1/4"	8'	96"	Wet	168,671	1,756

Table B-3

Bonneville Series 3 Test Results

Borehole Diameter Effects

Hole Number	Hole Diameter	Hole Depth	Grout Length	Water Condition	Max Load Pounds	Strength Per Inch
3-1	2-1/4"	5'	28"	Dry	60,563	2,162
3-2	2-1/4"	5'	26"	Dry	182,296	7,011
3-3	2-1/4"	5'	27.5"	Dry	68,830	2,502
3-4	2-1/8"	5'	32"	Dry	142,858	4,464
3-5	2-1/8"	5'	28.5"	Dry	100,188	3,515
3-6	2-1/8"	5'	29"	Dry	91,150	3,143
3-7	2"	5'	29.5"	Dry	65,435	2,218
3-8	2"	5'	23"	Dry	68,940	2,997
3-9	2"	5'	36"	Dry	75,021	2,083
3-10	2-1/4"	8'	26.5"	Dry	109,395	4,128
3-11	2-1/4"	8'	41"	Dry	165,682	4,041
3-12	2-1/4"	8'	35"	Dry	100,080	2,859
3-13	2-1/8"	8'	51"	Dry	113,516	2,225
3-14	2-1/8"	8'	48.5"	Dry	99,970	2,061
3-15	2-1/8"	8'	47"	Dry	196,748	4,186

Table B-4

Bonneville Series 4 Test Results

Borehole Diameter Effects

Hole Number	Hole Diameter	Hole Depth	Grout Length	Water Condition	Max Load Pounds	Strength Per Inch
4-1	2-1/4"	5'	31"	Wet	115,990	3,741
4-2	2-1/4"	5'	29"	Wet	113,760	7,011
4-3	2-1/4"	5'	26"	Wet	178,870	6,879
4-4	2-1/8"	5'	29"	Wet	69,660	2,361
4-5	2-1/8"	5'	33"	Wet	125,550	3,804
4-6	2-1/8"	5'	33"	Wet	150,420	4,558
4-7	2"	5'	36"	Wet	73,970	2,054
4-8	2"	5'	36"	Wet	41,550	1,154
4-9	2"	5'	36"	Wet	59,620	1,656
4-10	2-1/4"	8'	26.5"	Wet	109,395	4,128
4-11	2-1/4"	8'	41"	Wet	---	---
4-12	2-1/4"	8'	35"	Wet	113,140	3,232
4-13	2-1/8"	8'	51"	Wet	161,330	3,163
4-14	2-1/8"	8'	48"	Wet	115,230	2,375
4-15	2-1/8"	8'	47"	Wet	209,650	4,460

Table B-5

Bonneville Series B, L Test Results

Clean Large and Small Diameter Boreholes

Hole Number	Hole Diameter	Hole Depth	Grout Length	Water Condition	Max Load Pounds	Strength Per Inch
L-1	2-1/8"	8'	48"	Dry	214,122	4,408
L-2	2-1/8"	8'	48"	Dry	204,233	4,255
L-3	2-1/8"	8'	48"	Dry	205,330	4,277
L-4	2-1/8"	8'	48"	Dry	211,128	4,398
B-1	2-1/2"	8'	48"	Dry	203,118	4,229
B-2	2-1/2"	8'	48"	Dry	44,005	916
B-3	2-1/2"	8'	48"	Dry	175,498	3,656
B-4	2-1/2"	8'	48"	Dry	215,969	4,372

Table B-6

Bonneville Series T Test Results

Dynamic Water Boreholes

Hole Number	Hole Diameter	Hole Depth	Grout Length	Water Condition	Max Load Pounds	Strength Per Inch
T-1	2-1/8"	18'	96"	Wet	189,340	1,972
T-2	2-1/8"	18'	*	Wet	43,902	--
T-3	2-1/8"	18'	96"	Wet	222,497	2,317
T-4	2-1/8"	18'	**	Wet	---	--
T-5	2-1/4"	18'	139"	Wet	220,316	1,582
T-6	2-1/4"	18'	***	Wet	---	--
T-7	2-1/4"	18'	68"	Wet	215,098	3,163
T-8	2-1/4"	18'	73"	Wet	176,326	2,415

* Unable to measure grout length

** Anchor failed at seating load

*** Bearing surface prevented bolt stressing